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The purpose of this thesis is to provide a scheduling model to assign repairmen to standardized jobs in a utility company. The utility company studied is Columbia Gas Company which operates a service center for its repairmen in Columbus, Ohio. Two heuristic models are developed to do the required scheduling for the service center using deterministic parameters for cost, travel time, work time required and worker hours available. The first heuristic model employs a cost parameter which takes the current company assignment rules into consideration and makes assignments from the lowest cost to the highest cost. The second —

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heuristic model uses travel time for workers to travel to jobs as the criteria for making assignments. The worker with the lowest travel time to a job is assigned to that job, and workers continue to be assigned to jobs as their travel time becomes the lowest time available. Both heuristics are compared with the present method of the foremen making the assignments based on their past experience. The method of comparison employs historical data to accomplish both a cost analysis and a quality of assignments analysis. Both heuristic models reduce the cost of carrying out the assignments, but the quality of the assignments made is better using the first heuristic model which concentrates on following the current assignment rules of the company.

A Heuristic Model for Scheduling Repairmen to Jobs Using Deterministic Parameters

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Final Report 27 May 1980

Approved for public release; distribution unlimited.

A thesis submitted to The Ohio State University in Columbus, Ohio in partial fulfillment of the requirements for the degree of Master of Science in Industrial Engineering.

LV

A HEURISTIC MODEL FOR SCHEDULING REPAIRMEN TO JOBS USING DETERMINISTIC PARAMETERS

A Thesis

Presented in Partial Fulfillment of the Requirements
For the Degree Master of Science

by

Lester Francis McConville, B. S.

The Ohio State University
1980

Approved by

Gordon M. Clark

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CHAPTER I

INTRODUCTION

This chapter provides a statement of the problem as well as a description of the system in which it exists. Then a literature review is provided to give additional background for the problem, and the overall objectives of the thesis are explicitly stated. Finally, a chapter by chapter description of the thesis is stated.

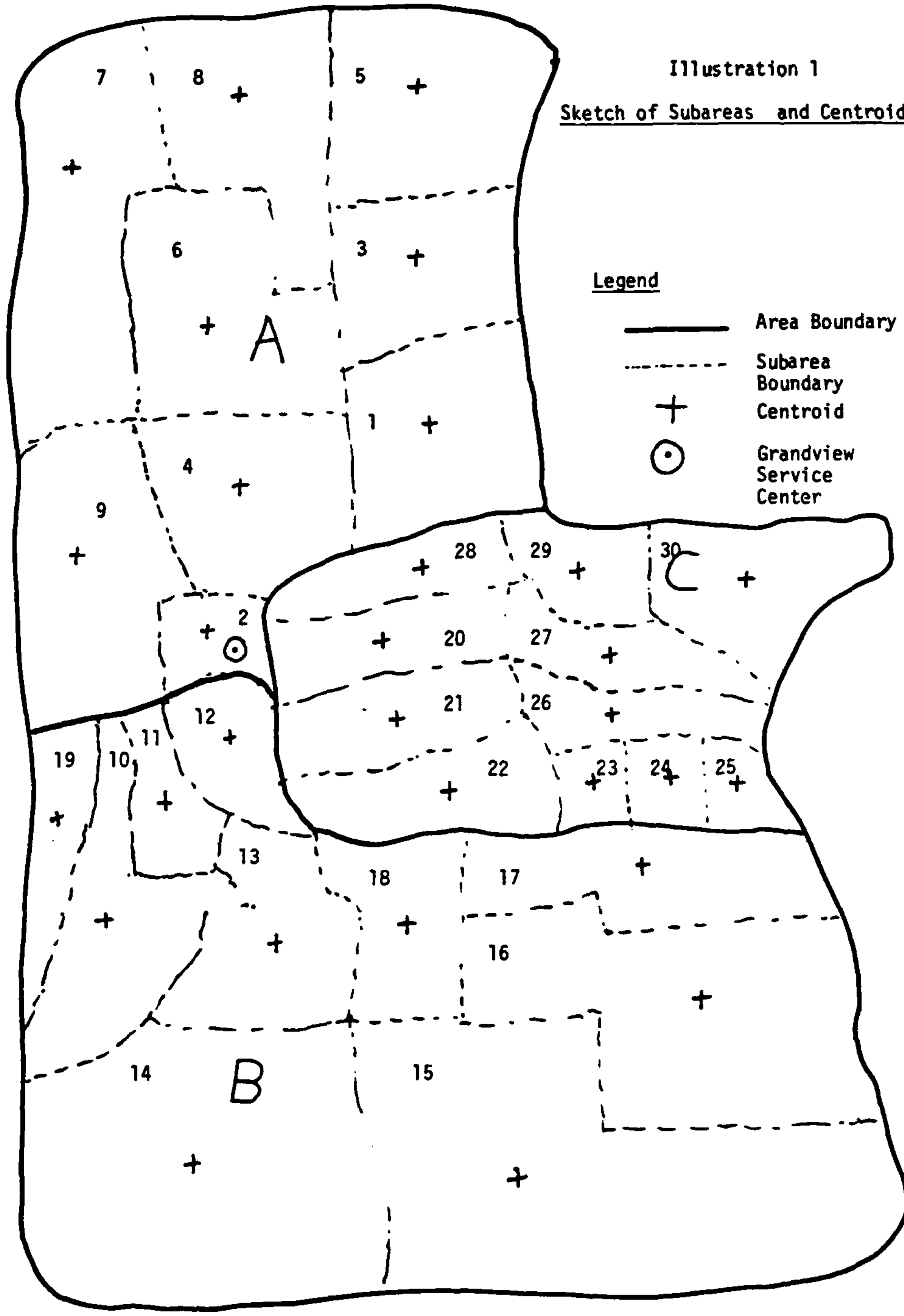
The general subject of this thesis is scheduling. Scheduling is a managerial function which involves arranging assets or activities in some sequence to accomplish an organizational goal. Included in this function are many varied tasks. In a machine shop, this would involve the foreman deciding which jobs will be run on which machines and in what order. Shipyard supervisors must decide in what order the activities to build a ship will be performed and which crews and materials will be necessary to do them. Hospital administrators are responsible for coordinating operating room staffs, doctors and patients. Possibly no function of management is more pervasive than scheduling because everything else that a manager does depends on how efficient and rational his scheduling efforts have been.

This thesis deals with a manager who is responsible for scheduling repairmen to jobs within a large metropolitan area. The metropolitan area is Columbus, Ohio, and the manager and his workers are assigned to the Grandview Service Center of Columbia Gas Company. This service center is solely responsible for completing all repairs in three of the five areas of Columbus which are designated areas A, B, and C with a foreman in charge of each of the areas. The areas are divided into subareas with a worker specifically assigned to each one. There are a total of thirty (30) subareas with nine (9) in area A, ten (10) in area B, and eleven (11) in area C. A sketch of the areas and subareas is contained in Illustration 1. In addition, there are workers called floaters assigned to each area. The floaters are used to complete any work in their area that the foreman desires. On a daily basis the repairmen handle between 350 and 500 repair jobs. The jobs all have standard operations which must be performed and are normally quite repetitious. The jobs relate directly to the gas meter or the lines monitored by the meter and do not involve such things as locating old gas lines or installing new ones.

Under the present system, the foremen do all of the scheduling by following a set of assignment rules. These rules have evolved

Illustration 1

Sketch of Subareas and Centroids



over time and have become agreeable to both workers and management. In fact, the workers look on them as binding on the managers and have threatened to unionize or strike over repeated violations. Whether or not these rules can be changed is not clear at the present time. The rules work in the following manner. The most senior repairman is allowed to pick the subarea he desires to be assigned in, and the next most senior individual then selects from the remaining subareas until all thirty (30) subareas have been assigned. The least senior individuals remain as floaters assigned to one of the three areas until one of the subareas has a vacancy due to retirement or other reasons. Then the floater with the most seniority is allowed to become assigned to that subarea unless one of the workers already assigned a subarea desires to move to the new one or he desires to remain as a floater until another subarea has an opening. These rules are used to establish the starting points and the status of all workers. The jobs are then assigned according to this status. In general, workers assigned to a subarea are only assigned to jobs inside that subarea even if there is not enough work to keep them occupied there. Floaters are only assigned jobs in their areas even if they are under-assigned, unless another area cannot accomplish all its jobs with its workers and floaters in

which case the floaters may be loaned. If the area still cannot accomplish its work, workers with assigned subareas in another area may be loaned. However, in reality, loaning rarely occurs, and the more general case is a lot of workers remain under-assigned.

The manager merely monitors the foremen's activities and provides them assets to accomplish the required tasks. The assets that are supplied to a foreman depend very much on the interpersonal skills of the foreman and, to a lesser degree, on the demand for work in his area. The principal reason for this is a lack of reaction time on the part of the manager. He does not know how much work must be accomplished on a given day until the foremen tell him on that day. Therefore, he parcels out the workers and their individual repair trucks based on past experience and personal relationships with the area foremen rather than on a verified need. This has been adequate in the past for two reasons. The most important reason is cost. Public utilities have never been very cost conscious entities because they have always been able to pass their operating costs on to the consumer with very little trouble. This happened because the operating costs could be spread over a very large number of customers who were paying a very minimal price for the actual consumable good or natural gas. With the dramatically increasing price

of gas, consumers, utilities, and governmental monitoring agencies have become more cost conscious. Now inefficiencies, such as excess workers, that were once acceptable, are not. The second reason this method was acceptable in the past is that the required work always was accomplished and still is being accomplished under the present system. Irrespective of how efficiently, the work gets done. Now there is not only pressure to get the jobs done, but also to schedule them in a more efficient manner and to do them with fewer assets.

Prior to changing the old system, an understanding of how it operates should be gained. Possibly the best way to comprehend how the present scheduling system works, is to trace one job through the system. The job will be requested over the telephone to one of the customer service operators. These operators ask the customer required information such as their account number or name and specific repair problem. The operator then types in the account number and receives a display on a Cathode Ray Tube (CRT) of information pertinent to the account such as meter number and subarea. Next, the operator assigns the job a specific date to be done which is normally the date the customer requests or the day that has the least number of jobs to be done within the next ten (10) days.

However, the job will not be scheduled on a day when the total number of jobs exceeds a limit set by the service center manager. This limit remains at a constant figure unless the manager changes it due to mitigating circumstances such as a reduction in his work force due to sickness. Once the date is assigned by the operator entering it on the CRT, the information is transmitted to the computer and a work order is generated.

Once the work order is printed by the computer, it is filed by a clerk chronologically by the day it is to be performed and then sorted by area containing the job location. At approximately 6:00 a.m. the day the job is to be done, the foreman for the area it is in picks it up along with all the other jobs in his area for the day. Sometime between 6:00 a.m. and 8:00 a.m., the foreman assigns the job to a specific worker or floater. At 8:00 a.m., the worker picks up the work order at the service center from the foreman along with all his other jobs. The worker takes all the orders and fills out a route list which indicates the order in which he intends to perform the services. Essentially, the jobs are all of equal importance so he just picks a logical route to complete all the jobs and will normally attempt to have the last job on his route as close to his own home as possible since he is allowed to travel

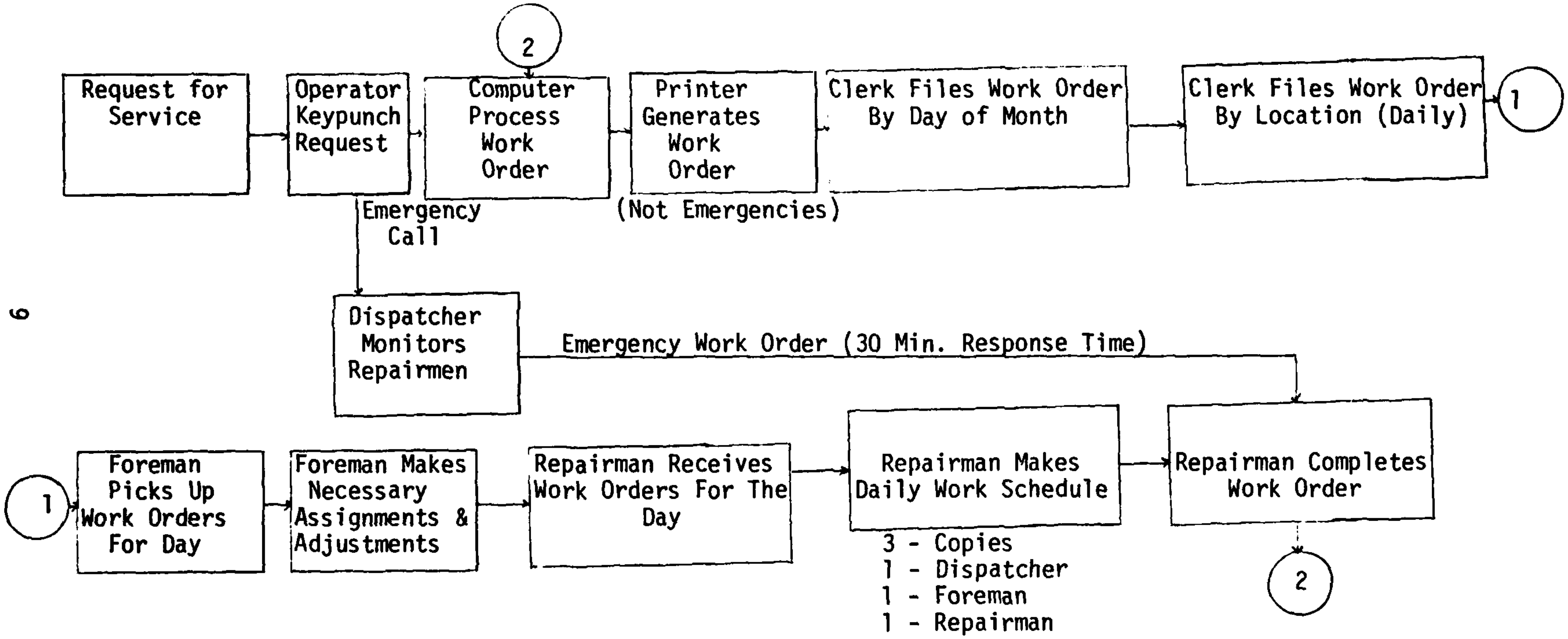
directly home after his last job if it is close to quitting time.

The route list is filled out in triplicate with one copy each going to the foreman, the worker and the dispatcher. A copy goes to the dispatcher because this individual is in radio contact with the worker and is able to transmit emergency work orders to the appropriate worker since the route list provides him detailed worker locations. These emergency work orders take priority over the schedule for the day and must be answered within 30 minutes unless a fire has occurred in which case an immediate response by the closest repairman is required by law. The dispatcher also monitors the worker's progress during the day and turns in the route list as a report of the activities accomplished by the worker. In addition, the worker turns in a copy of the work order for the job which indicates any actions he took on the job and whether or not it was completed. If it was not completed, the job is recirculated through the system on another day. However, most jobs are completed as scheduled. Illustration 2 presents a flow-chart depicting the present system operating procedures.

The problem then is modify the present system so that it can accomplish the same tasks but in a more efficient manner. This efficiency can be gleaned from using the information presently in

Illustration 2

Columbia Gas Repairmen Work Order Flowchart



the computer more effectively; by reducing the amount of time foremen must spend doing scheduling tasks; by reducing the number of repairmen or amount of time the workers spend completing these tasks; by reducing the total distance traveled to all jobs; and finally, by providing the service center manager with useful information so he can plan the operation of the overall system rather than just react to events as they occur. The planning that the manager must do involves several aspects. The first is how many workers he needs for his service center for the day. If he is overloaded, he may need to request help from another service center. The second is how many repairmen to allocate to each area. At the present time, there is a standard number assigned to each area, but he may need to change this based on demand. The last is whether to perform additional work for the day. He normally has a backlog of work that can be assigned at his discretion in order to fill in slack time. He must decide when it is appropriate to assign this work and to whom it should be given.

In order to solve this particular scheduling problem, a review of the scheduling literature was conducted with the objective of finding a useful model. Scheduling problems are fairly common in the literature but scheduling models to solve these problems

and scheduling theory as a whole remains relatively underdeveloped when it is compared to other areas of operations research such as inventory control. The most studied problems in scheduling are small job shop algorithms which can be used to schedule a small number of jobs on a few machines in an optimal fashion with respect to various regular performance measures such as flow-time or lateness as discussed in Conway (1967). The most important concept to evolve out of this sequencing theory is called shortest-processing-time, and it is very often used to produce either optimal or good solutions to these job shop problems. Enumeration of all possible alternatives is also discussed in Conway (1967) as a method of solving scheduling problems, but as the problems get larger this method quickly becomes impractical. One extension of the shortest-processing-time principle is discussed in Baker (1974) and is called the closest-unvisited-city algorithm. This algorithm is a heuristic procedure which may be used to solve the traveling salesman problem. Another procedure used to solve this same scheduling problem of the sequence in which a salesman should visit cities along his route in order to minimize his overall travel time is integer programming. However, integer programming is noted for its inability to solve large problems efficiently. For

example, a traveling salesman problem was run on an IBM 360 for one salesman visiting 100 cities, and the run time on the computer using a branch and bound algorithm to solve the integer program took over fifty (50) minutes as reported by Garfinkel (1972). The overriding theme in scheduling literature seems to be that small problems can often be solved in an optimal fashion, but the larger and more complex the problem becomes, the more impractical it becomes to look for optimal solutions. In these problems, heuristics are very often applied which use concepts developed in sequencing theory and other logical approaches to generate efficient solutions. There are numerous examples of heuristics being applied to solve these problems such as Browne's (1978) article which applies an arithmetic heuristic to manpower scheduling or Canter's (1976) article which develops a heuristic method to schedule patients to visit doctors based on some expected completion times for caring for different categories of patients. However, nowhere in the literature was there found a model which would solve the scheduling problem of interest which is to assign gas repairmen to jobs at a reduced cost while complying with the assignment rules. Yet concepts found there may be of some use in developing a model to solve this particular problem. What is needed is a heuristic model

or models that take advantage of the computer system at Columbia Gas by using it to generate feasible assignments for all the repairmen. The heuristic should employ some of the concepts found in the literature in an inventive and logical fashion.

From the problem statement and the available literature, it is possible to define reasonable objectives for the model to fulfill. First the model should employ the data that is presently on the computer plus some additions and have a short run time. Second, the model should provide the manager with three items of information by the afternoon prior to the work being done. These items are; the assignments for all workers, an estimate of the number of hours each worker has available after completing his assignments and a cost estimate for completing all jobs to include travel costs. Third, the model should improve the overall efficiency of the scheduling system. This can be done by reducing the amount of time foremen spend on making assignments, reducing the man hours required to carry out all the assignments and by reducing the travel costs associated with the schedule. Lastly, the model should make realistic assignments when compared with the present system, which means that the assignment rules should be followed as closely as possible.

The remainder of this thesis attemps to accomplish these objectives. Chapter II describes the parameters involved in the solution methods and outlines a methodology for calculating each one. At the end of the chapter, a mathematical model is stated for illustrative purposes only and no solution method for it is proposed. Chapter III discusses the two proposed heuristic solution methods to the scheduling problem. The first heuristic method discussed attempts to mimic the present system by following all the assignment rules presently in effect. However, it attempts to do this more efficiently when possible. The second heuristic method discussed emphasizes cost reductions and allows the present assignment rules to be violated. A computer program is presented to solve both heuristic methods and a small example problem illustrates the basic differences between the methods. Chapter IV analyzes the performance of the heuristic methods by comparing both of them with the present method of having the foremen make all the assignments on their own. Historical data is used to make the comparisons. The first comparison is to contrast the total cost of the assignments. The second comparison involves the quality of assignments and how well each of the heuristic methods follow the assignment rules. Chapter V provides a recommendation on which

method to implement and how. It also provides ideas for possible applications for the model and directions for future work.

CHAPTER II

MODEL DEVELOPMENT

This chapter describes the parameters necessary for inclusion in possible solution methods. These include a cost parameter, a standard work time parameter, a travel time parameter, a worker hours available parameter and a job location parameter. Each of these is discussed in detail and a methodology for calculating each one is outlined. Finally for illustrative purposes a non-linear zero-one mathematical programming model is stated. Prior to discussing each of the parameters individually, they will be discussed as a group and defined individually.

The first parameter is the cost parameter, c_{ij}, and is defined as the cost of sending worker i to subarea j. The second parameter is the standard work time parameter, r_k. It is defined as the expected time to complete a job of type k. The third parameter is t_{ij}, and it is the travel time parameter. Its definition is the amount of time it takes worker i to travel to subarea j. The fourth parameter is h_i, and it is the worker hours available parameter. It is defined as the hours worker i has available for assignment to jobs. The last parameter is q_j, and it defines the

number of jobs to be done within a subarea. Its definition then is the total number of jobs in subarea j. It is assumed that all of these values are deterministic. In this particular case, this assumption makes sense because the demand or number of jobs to be scheduled is known in advance as well as their locations and types, and with this knowledge, an expected value solution can be generated. Several other characteristics of these parameters make this a logical assumption, and these will be discussed along with each of the parameters.

In order to define the cost parameter, an understanding of the assignment rules that serve as a basis for the cost parameter is important. These rules state that assignments are to be made in the following sequence:

1. Workers to jobs in their assigned subareas.
2. Floaters to jobs in subareas contained by their assigned areas.
3. Closest workers to jobs within the area containing their respective assigned subareas.
4. Floaters to jobs in subareas not contained within their assigned areas.
5. Closest workers to jobs not within the areas containing their assigned subareas.

In order to accommodate these rules within the cost parameter, a variable needs to be introduced which will measure how close various workers are to a given job. This variable is d_{ij} and is defined as the straight line map distance between the start point for worker i and the centroid of subarea j. The centroid of the subarea is an estimated point near the geometric center of the subarea from which all trips into or out of the location are assumed to originate or terminate. A sketch of the subareas, areas and their centroids is included as Illustration 1. The start point for worker i is also the centroid of his assigned subarea except in the case of the floaters, and the start point for all of them is the service center location. The various values of d_{ij} are listed in Appendix 1. It is now possible to define a cost parameter, c_{ij}, which is not a true cost but rather is a mechanism by which assignments can be made according to the set of assignment rules. C_{ij} consists of the sum of three other variables which are based on d_{ij} and will cause all assignment rules to be followed if c_{ij} is minimized. The first variable is G_{ij} and is the cost associated with assigning worker i to a job in subarea j. This variable deals only with the first and third assignment rules where the worker is being assigned within his own area. If he is being assigned to his

own subarea, then that is the most preferred situation and no cost should be incurred. If he is being assigned to another subarea, then he should be assigned according to how close his subarea is to subarea j with respect to the other workers in the area. This can be accomplished using the d_{ij} parameter. Therefore, G_{ij} is defined as follows:

$$G_{ij} = \begin{cases} d_{ij} & \text{If worker i is not a floater and subarea j is in worker i's area but not in worker i's subarea.} \\ 0 & \text{If otherwise.} \end{cases}$$

The second variable is F_{ij} and is the cost associated with assigning floater i to a job in subarea j when the subarea is contained within the floater's assigned area. This variable relates only to the second assignment rule where the floater is being assigned within his own area. The value of F_{ij} is sensitive only to workers assigned to subareas in the area under consideration. Therefore, the value of F_{ij} must be greater than 0 which is the cost of assigning a worker within his own assigned subarea and must be less than the minimum d_{ij} for the subarea under consideration where d_{ij} does not equal 0. If I_a represents the set of all workers assigned to area a or $I_a^* = \{i \text{ assigned to subareas in area } a\}$, then

$$\text{let } \alpha_j = \underset{\substack{i \in I_a \\ j \in \text{area } a}}{\text{Minimum}} \; (d_{ij} : d_{ij} > 0)$$

This means that α_j is the minimum distance for all workers assigned subareas in area a to get to subarea j. Since the floaters assigned in the area, must be assigned prior to any other workers, it is necessary to reduce α_j by 1 so no tie exists in subarea j between a floater and the worker i with the minimum d_{ij} value. Therefore F_{ij} is defined as follows:

$$F_{ij} = \begin{cases} \alpha_j - 1 & \text{If worker i is a floater and subarea j is in worker i's assigned area.} \\ 0 & \text{If otherwise.} \end{cases}$$

Also α_j must be greater than or equal to 2 to avoid erroneous results when 1 is subtracted from it.

The third variable is E_{ij} and is the cost associated with assigning worker or floater i to a job in subarea j when the subarea is not contained within the repairman's assigned area. This variable relates to the fourth and fifth assignment rules where the repairman is being assigned outside his own area. In order to comply with the first three assignment rules, it is necessary for the value of E_{ij} to be higher than either F_{ij} or G_{ij} for the subarea j under consideration. It must also reflect the fact that a floater

from an area not containing the subarea j must be assigned prior to a worker from that same area in order to comply with the fourth and fifth assignment rules. If I_j^* represents the set of all workers assigned to subareas not in area a which contains subarea j or

$$I_j^* = \left\{ i \text{ not assigned in the area a that contains } j \right\},$$

then let $\Delta_j = \underset{\substack{i \varepsilon I_j^* \\ j \varepsilon \text{ area a}}}{\text{Minimum}} (d_{ij})$ and $\beta_j = \underset{\substack{i \varepsilon I_a \\ j \varepsilon \text{ area a}}}{\text{Maximum}} (d_{ij})$.

This means that Δ_j is the minimum distance for the set of all workers assigned subareas not in area a to get to subarea j, and β_j is the maximum distance for all workers assigned subareas in area a to get to subarea j. With these definitions, it is possible to define E_{ij} such that the assignment rules will not be violated when the three variables are summed and the cost minimized. Therefore, E_{ij} is defined as follows:

$$E_{ij} = \begin{cases} \beta_j + \Delta_j - 3 & \text{If worker i is a floater and subarea j is not in worker i's assigned area.} \\ \beta_j + d_{ij} & \text{If worker i is not a floater and subarea j is not in worker i's assigned area.} \\ 0 & \text{If otherwise.} \end{cases}$$

Also both β_j and Δ_j must be greater than or equal to 4 to avoid erroneous results when 3 is subtracted from their sum. Since C_{ij}

is the sum of the three variables, $C_{ij} = G_{ij} + F_{ij} + E_{ij}$. With C_{ij} defined in this way, by minimizing cost the assignment rules will be followed with an objective function value of 0 if all jobs can be given to workers in their assigned subareas and no floaters are used. More importantly, by defining C_{ij} in this manner, it is possible to determine the costs of all jobs to be assigned and then make assignments from the lowest C_{ij} to the highest. This will ensure that all rules are followed given that the jobs were considered in a sequential fashion and not simultaneously. A list of C_{ij} values is contained in Appendix 2.

The second parameter is r_k which is the standard work time for each job of type k. There are four basic job types which are performed by the repairmen. Type 1 is turning on and off gas service and involves both physically shutting off or turning on the gas and making standard tests. Over 57% of all the jobs done in 1979 were of this type. Type 2 involves investigations of customer complaints, such as bills being too high. Normally, this job involves testing the gas meter to insure it is correctly registering and discussing the results with the customer. On the surface, it would appear that these customer discussions might cause a great deal of variance in the standard work time. However, the repairman only reports his

findings and does not engage in extensive arguments, but will make a referral to another specialist and move on to the next job. Type 3 is making new installations. The moratorium on new gas customers was lifted in late 1979, and in the future this type of job will become more prevalent. In making new installations, the repairman is responsible for testing the gas lines, emplacing the gas meter and turning on the gas. Type 4 is comprised of various maintenance services of the gas meter itself, such as changing the meter. There are established standard work times for each of these job types. These times are the times in which the company expects all repairmen to complete each job type and are listed in Table 1.

Table 1

Standard Work Times

JOB TYPE	JOB NAME	r_k (Completion Time)
1	Turn On and Off	.33 hours
2	Investigations	.50 hours
3	New Installations	.83 hours
4	Meter Maintenance	.25 hours

Additional confidence was gained in these standard work times when data for the calendar year 1979 was analyzed. These data showed

that these work times are probably accurate; however, this could not be used to verify the times since the data sometimes contained travel times. Additionally the methodology for collecting these data could not be verified. All jobs have the same priority for accomplishment with the exception of type 1 jobs which should be attempted by the repairman before other job types. One adjustment must be made to the r_k parameter to account for work that is scheduled but not actually performed. This is usually due to the repairmen not being able to gain access to the building or house in which the gas meter is located. In 1979, 10.1% of the job locations were visited, but the jobs not actually performed. This figure appears to be quite stable and has very little variance from month to month or worker to worker. Therefore, it can be used as a constant to reduce the actual worktime expended when jobs are scheduled. After this adjustment, the work time parameter, r_k, is a reliable parameter able to be used to define the amount of work time expended.

The third parameter is the travel time, t_{ij}. This is the amount of time it takes the worker i to depart from his location and start work at a job in another subarea j. His location or subarea may vary throughout the problem, but always depends on where he was located for the previous job. Basically, there are two parts to

this parameter. The first one is the total trip end time and that is all the time the trip takes excluding the actual driving done outside the immediate area of the new job and the worker's old location. This would include such things as walking to the repair truck after completing a job and driving around looking for a parking place at a new job site. The time spent driving around on streets in the immediate area of the new job and the worker's old location is called local street time. All other time spent in total trip end time is terminal time. The second part is the actual time the worker spends driving the vehicle outside the immediate neighborhood of the new job or his old location. The methodology used to determine the travel times is based on a report published by the Transportation Research Board (1978). It is felt that this methodology provides excellent approximations for the actual travel times for several reasons. First, in a thesis Jewett (1980) studied how to determine the best place to locate a service center for the repairmen and found that the best way to estimate travel times was by using this methodology. Second, as part of the validation process, the Transportation Research Board (1978) applied the model successfully in Columbus. Last discussions with Professor Mekemson (1980), an expert in transportation models, revealed he felt

that this particular method was one of the best available and was applicable in most United States cities. This wide applicability is important as a successful model and should be able to be used in various cities around the country with only minor modifications.

In order to use this method, the city is partitioned into three regions. These regions are the central business district (CBD), the central city, and the suburb. The smallest region of the city is the CBD and is the downtown area. In the city of Columbus, this area is rather well defined by the inner belt loop formed by interstate routes 70 and 71. The central city is the residential and commercial region and lies between the CBD and the suburb. Normally, this will lie within a circumferential highway system, and for the city of Columbus, this is Interstate Route 270. The outermost region is the suburb which consists of mostly residential and rural areas lying outside the central city. A sketch of the regions and freeways is given in Illustration 3, with freeways being high speed limited access highways and everything else being arterials. This will allow classification of each of the 30 subarea into one of the three categories. This categorization appears in Table 2.

Illustration 3

Regions of Columbus and Freeways

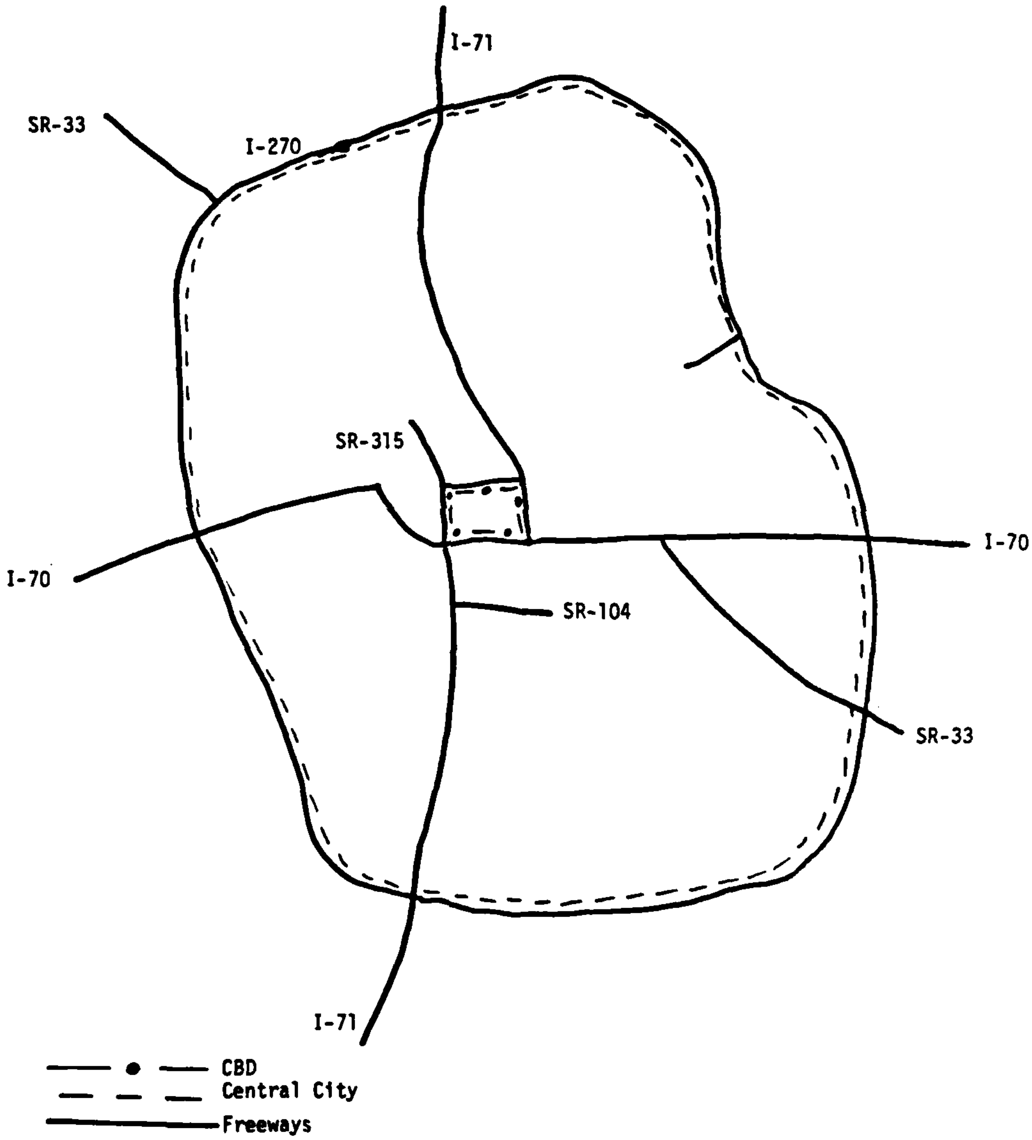


Table 2

Categorization of Subareas

REGION TYPE	SUBAREA
Central Business District	22
Suburb	7, 9, 14, 15
Central City	25 remaining subareas

The categorization was based on which region the majority of the subarea's land mass fell within. For example, subarea 7 has part of its area within the central city and part in the suburb, but since the majority is in the suburb, it is classified suburban.

The next item necessary to calculate travel times is the straight line map distance between the worker's start points and the centroids of all the subareas. The d_{ij} parameter remains as defined before but is measured in miles. The d_{ij} matrix listed in Appendix 1 can be converted to miles by dividing by the reference map's conversion factor of 35 millimeters per mile. The converted matrix can be changed to actual driving distances by multiplying each element in it by 1.22 which is the assumed circuity factor for the Columbus area. This circuity factor has been found to range between 1.20 and 1.40 in various cities around the country.

For rather level cities, such as Columbus or Lincoln, Nebraska, the factor would be near the lower end of the spectrum, and for cities, such as San Francisco that have many hills, it would approach 1.40. An adjustment of this circuity factor would need to be made depending on the location in which the methodology was being applied.

Other values needed in the computation of travel times are the trip end conditions and speeds within regions. These items were derived by the Transportation Research Board (1978) from various other transportation studies and are contained in Tables 3 and 4.

Table 3

Trip Ends for Cities of 100,000 Population and Above

	CBD	Central City	Suburb
Terminal Time (Minutes)	6	3	1
Local Street Distance (Miles)	.0625	.1875	.5000
Local Street Speed (MPH)	11	15	25
Local Street Time	.34	.75	1.20
Total Trip End Time (Terminal Time + Local Street time in minutes)	6.34	3.75	2.20

SOURCE: Transportation Research Board

Table 4

Speed for Cities Between 250,000 and
750,000 Population in Miles Per Hour (MPH)

	CBD	Central City	Suburb
Arterial	15	22	30
Freeway	36	40	48

SOURCE: Transportation Research Board

With the information presented so far, it is possible to calculate the travel times individually. For example, consider a worker traveling from subarea 7 to subarea 6 which involves moving from a suburban subarea to a central city subarea. The calculation for t_{76} would be as follows:

Distance Calculations

1) Over-the-road distance in subarea 7
   3.45 x 1.22 = 4.21 miles

2) Distance in subarea 7 on local streets
   Table 3 = .50 miles

3) Distance on arterials in subarea 7
   Equations 1 - 2 = 3.71 miles

4) Over-the-road distance in subarea 6
   1.69 x 1.22 = 2.06 miles

5) Distance in subarea 6 on local streets

Table 3 = .19 Miles

6) Distance on arterials in subarea 6

Equations 4 - 5 = 1.87 Miles

Time Calculations

7) Time on local streets in subarea 7

Table 3 = 1.20 Minutes

8) Time on arterials in suburb subarea 7

$$\frac{3.71 \text{ miles}}{30 \text{ mph}} \times 60 \text{ min/hr} = 7.42 \text{ Minutes}$$

9) Terminal time in subarea 7

Table 3 = 1.00 Minutes

10) Total time in suburb (subarea 7)

Equations 7 + 8 + 9 = 9.62 Minutes

11) Time on local streets in subarea 6

Table 3 = .75 Minutes

12) Time on arterials in subarea 6

$$\frac{1.87 \text{ miles}}{22 \text{ mph}} \times 60 \text{ min/hr} = 5.10 \text{ Minutes}$$

13) Terminal time in subarea 6

Table 3 = 3.00 Minutes

14) Total time in central city (subarea 6)

Equations 11 + 12 + 13 = 8.85 Minutes

15) Total trip time

Equations 10 + 14 = 18.47 Minutes

Two possible extensions to these travel time calculations must be discussed. First of all, it is very possible that not all of the travel between subareas will be done on arterials. Freeways will often be used, and when they are, the percentage of time the freeway is used in a subarea must be estimated. This is done by looking at the most likely route the worker will take between his start point and his terminal point, and estimating what percentage of the time the worker will spend on the freeway as he crosses the subarea under consideration. The calculations are then made in the same manner as before; however, the distance traveled in the subarea under consideration is divided appropriately between freeways and arterials which in turn effects the calculation of the travel times.

The second extension involves the calculation of travel times within subarea or intra-subarea travel. In order to calculate these travel times the intra-subarea straight line distance must be calculated. This is done by determining all the subareas that are adjacent to the subarea under consideration and measuring the straight line distance to them. These distances are then summed and divided by the number o, adjacent subareas. This number is divided in half to give an estimate of the straight line distance. The measuring figure can be multiplied by the circuity factor to determine over-

the-road distances if necessary. For example, there are five (5) subareas adjacent to subarea #20. These subareas are #2, #4, #21, #27, and #28 with respective straight line distances of 2.06 miles, 2.26 miles, .80 miles, 1.86 miles, and .91 miles. The sum of all the straight line distances is 7.89 miles which must be divided by five (5) to give a result of 1.58 miles. This number, 1.58 miles, is divided in half to give the intra-subarea straight line distance for subarea #20 which is .79 miles. A list of all the intra-subarea straight line distances is given in Table 5.

Table 5

Intra-Subarea Travel Distances (Miles)

SUBAREA	DISTANCE	SUBAREA	DISTANCE
1	1.23	16	1.30
2	1.38	17	.80
3	1.55	18	1.29
4	1.35	19	1.00
5	1.50	20	.79
6	1.93	21	.70
7	2.87	22	.92
8	2.52	23	.61
9	2.68	24	.43
10	1.30	25	.52
11	1.51	26	.63
12	1.06	27	.85
13	1.60	28	.78
14	2.61	29	.78
15	2.60	30	1.19

From this point on these distances are treated like any other straight line distances and are used to calculate the intra-subarea travel times. In order to simplify these rather tedious calculations, straight line distance versus travel time graphs and tables are listed in Appendix 3. From these graphs a travel time matrix has been constructed and is included as Appendix 4. One minor addition was made to this methodology and that was the assumption that t_{ij} is always greater than t_{ii}. Essentially this assumption states that it is always quicker to travel to a job from within the subarea than from an outside subarea. In almost all cases the calculations bore this out; however, in the case of subareas, such as #10 and #19, where geometry placed the centroids of the subareas quite close, the methodology generated travel times which indicated that it was quicker for the worker in subarea #19 to travel to a job in subarea #10 than it was for the worker assigned to subarea #10. Since the assumption is that t_{ij} is greater than t_{ii}, any t_{ij}'s violating this assumption were incremented slightly so that their value was six (6) seconds higher than t_{ii}. This assumption was designed to reduce inconsistencies thereby providing more realistic travel times. Overall, the methodology performed quite well and generated very realistic travel times.

The fourth parameter is h_i which is the hours that worker i has available to be assigned. This would seem, at first glance, to be a rather trivial deterministic parameter to calculate, and in essence it is, but several adjustments to this parameter need to be made before it is appropriate for use in a scheduling algorithm. First of all, workers are paid for an eight (8) hour day, but through agreement all of them only work 7.5 hours and take no breaks or lunch hour. Next, every worker must have enough time available to work an emergency call if the dispatcher calls him; therefore, it is necessary to reduce each worker's hours by the work time required for an investigation or type 2 job since this is the work time necessary for an emergency job. Additionally, the travel time, t_{ij}, to the emergency job must be subtracted from the worker's hours. For the workers assigned a subarea, this will be the t_{ij} associated with the intra-subarea travel time for that worker since an emergency call will most likely be within the worker's assigned subarea. For floaters, it is safest to subtract the maximum intra-subarea travel time since it is not possible to determine beforehand which subarea the floater will be in when the emergency call comes in for something like an odor of gas.

The last adjustment involves getting all the workers to their

start points. In the instance of the floaters, their start point is the service center location so that no adjustment is necessary, but with workers assigned a subarea, this is not true. Workers assigned a subarea must travel from the service center location to their assigned location. Therefore, it is necessary to reduce their hours available by the difference between the travel time from the service center location to the subarea and the intra-area travel time for the subarea. The hours that remain after these adjustments are the times that the workers have available for scheduling given that the floaters start work at the service center, and the other workers start work in their assigned subareas. The last parameter is q_j and is merely the total number of jobs in subarea j. The total number of jobs is known before scheduling begins, and since the location of each job is known, it is a fairly simple matter to determine the total number of jobs in each subarea.

With the parameters of the model stated, it is now possible to present a possible mathematical formulation of the problem. Start by defining the independent zero-one variable Z_{imjk} as follows:

$$Z_{imjk} = \begin{cases} 1 & \text{If the mth job for worker i is in subarea j and of type k.} \\ 0 & \text{If otherwise.} \end{cases}$$

And Z_{iojk} is the start point or initial condition for the worker i. The subscript i can assume values from 1 to M with M being the total number of workers available in the system. Subscript m can assume values from 1 to M* with M* being an upper limit on the number of jobs a worker can perform. Subscript j can assume values from 1 to L with L being the total number of subareas. Subscript k can vary from 1 to P which is the total number of different job types. Then by letting t_{jg} be the travel time between location j and g, the model can be stated as follows:

Minimize

$$\sum_{k=1}^{P} \sum_{i=1}^{M} \sum_{j=1}^{L} \sum_{m=1}^{M^*} Z_{imjk} \cdot C_{ij}$$

Subject to:

1) $$\sum_{k=1}^{P} \sum_{m=1}^{M^*} \sum_{j=1}^{L} \sum_{g=1}^{L} Z_{imjk} \cdot Z_{i,\, m-1,\, gk} \cdot t_{jg} + \sum_{k=1}^{P} \sum_{m=1}^{M^*} \sum_{j=1}^{L} r_k \cdot Z_{imjk} \le h_i \quad i=1,\ldots M$$

2) $$\sum_{k=1}^{P} \sum_{i=1}^{M} \sum_{m=1}^{M^*} Z_{imjk} \geq q_j \qquad j=1,\ldots.L$$

3) $$Z_{imjk} = \begin{cases} 1 & \text{If the mth job for worker i is in location j and of type k.} \\ 0 & \text{If otherwise.} \end{cases}$$

This model has three sets of constraints. Constraint set 1 is used to ensure that a worker will have enough time to complete all jobs assigned to him. Constraint set 2 ensures that all jobs in a sub- [illegible] will be assigned. The last constraint ensures that only whole [illegible] be assigned. It must be noted that this model will have a large number of integer variables and is nonlinear due to the effects of travel time which requires that the sequence of the jobs must be specified in order to calculate them. Essentially this model may be helpful in understanding the problem but is quite difficult to solve. Therefore, heuristic solution procedures to solve this mathematical model will be explored in the following chapter using the parameters c_{ij}, r_k, t_{ij} and h_i as they were discussed in this chapter.

Chapter III

SOLUTION METHODS

This chapter describes two solution methods which generate schedules assigning gas repairmen to jobs. In addition, the chapter presents an example problem which is solved by both methods and the results compared. The first solution method presented in this chapter emphasizes scheduling jobs in a manner comparable with the present system. It attempts to follow the rules presently in effect while using the workers and their trucks in an efficient manner. The idea for this solution method came from the shortest-processing-time principle as discussed in Conway (1967). This principle simply says to schedule the jobs sequentially so that the job that takes the least amount of time to perform is done first, and the rest of the jobs are done in order according to which takes the shortest-processing-time. Although the processing time of the jobs is not the critical aspect of the scheduling problem under consideration, the concept will be applied to the cost parameter in an attempt to obtain a good solution.

Rather than selecting the job that takes the least amount of processing time, a heuristic was devised that schedules the job

with the smallest cost, c_{ij}, first and other jobs in ascending order according to their respective costs. Additionally, each assignment is checked for feasibility prior to making the assignment. Feasibility is determined by whether or not the worker has enough time remaining to travel to the job and do the work required for the entire job at its location. One point of emphasis is that this method looks at the jobs one at a time rather than simultaneously; therefore, no claim of optimality can be made. Yet, the c_{ij} parameter was specifically designed so that if jobs were assigned from a lowest cost to a highest cost, then the rules governing assignment of workers will be followed given that the jobs were considered in a sequential fashion. This interaction between the cost parameter and the heuristic are the key to its functioning. The solution generated should be one that conforms to the standards set under the present system and also be a feasible one since feasibility is checked before each assignment is made.

This solution method is labeled the "smallest cost" method for ease in reference and to distinguish it from the other method which will be discussed later in this chapter. The heuristic employed in the smallest cost method has ten (10) steps and employs the same parameters and notation as given in Chapter II with several

additions. NC_{ij} is the current cost of worker i going to subarea j and is equal to C_{ij} initially. Nt_{ij} is the current travel time of worker i going to subarea j and is equal to t_{ij} initially. Both of these parameters are used to reflect the change in the cost and travel times as assignments are made and workers move from their start point to the subareas where the assigned jobs are located. S is a constant value larger than the maximum C_{ij} value. It is used in the heuristic to eliminate either workers or subareas from consideration. In addition, each job is identified by a job number n. Each job number has associated with it a job type k and subarea j. The steps for the heuristic are listed in Table 6 and a flowchart is included as Illustration 4. All notations used in the heuristics is defined in Table 7.

Table 6

Smallest Cost Method

(A Heuristic Procedure for Minimizing Cost)

STEP 1	Determine the minimum NC_{ij} where i=1,...M and j=1, ...L. Then set i equal to the worker and j equal to the subarea associated with the minimum NC_{ij}.
STEP 2	If the minimum NC_{ij} = S, STOP.

Table 6 Smallest Cost Method (Continued)

STEP 3 For subarea j, determine if a job exists. If so, record the job as job number n and determine the standard work time for a job of its associated type k, i.e., r_k. If not, set $NC_{ij} = S$ for i=1, ...M and go to STEP 1.

STEP 4 If worker i has enough hours available, h_i, to complete all the remaining jobs in subarea j, go to STEP 7. Otherwise, investigate all other workers who have an equal current cost value for subarea j to determine if any of them have enough hours available to complete all jobs in subarea j. For the first worker p who meets this requirement, set i=p and go to STEP 7.

STEP 5 Investigate all workers who have an equal current cost value for subarea j and select the worker p who has the most hours available, h_p. Set i=p.

STEP 6 If worker i's hours, h_i, are greater than or equal to $r_k + Nt_{ij}$ for job number n, go to STEP 7. Otherwise let $NC_{ij} = S$ and if every $h_p < r_k + Nt_{pj}$ for p=1, ...M delete job number n from consideration and record it as an overtime requirement. Go to STEP 1.

STEP 7 Reduce h_i by $r_k + Nt_{ij}$.

STEP 8 Assign job number n to worker i in subarea j and delete job number n from consideration.

STEP 9 Set $Nt_{iy} = t_{jy}$ for y=1, ...L. If worker i is not a floater, set $NC_{iy} = C_{jy}$ for y=1, ...L.

STEP 10 Determine if a new job number n exists in subarea j. If it does, go to STEP 6. Otherwise go to STEP 1.

Illustration 4

Flowchart of Smallest Cost Method

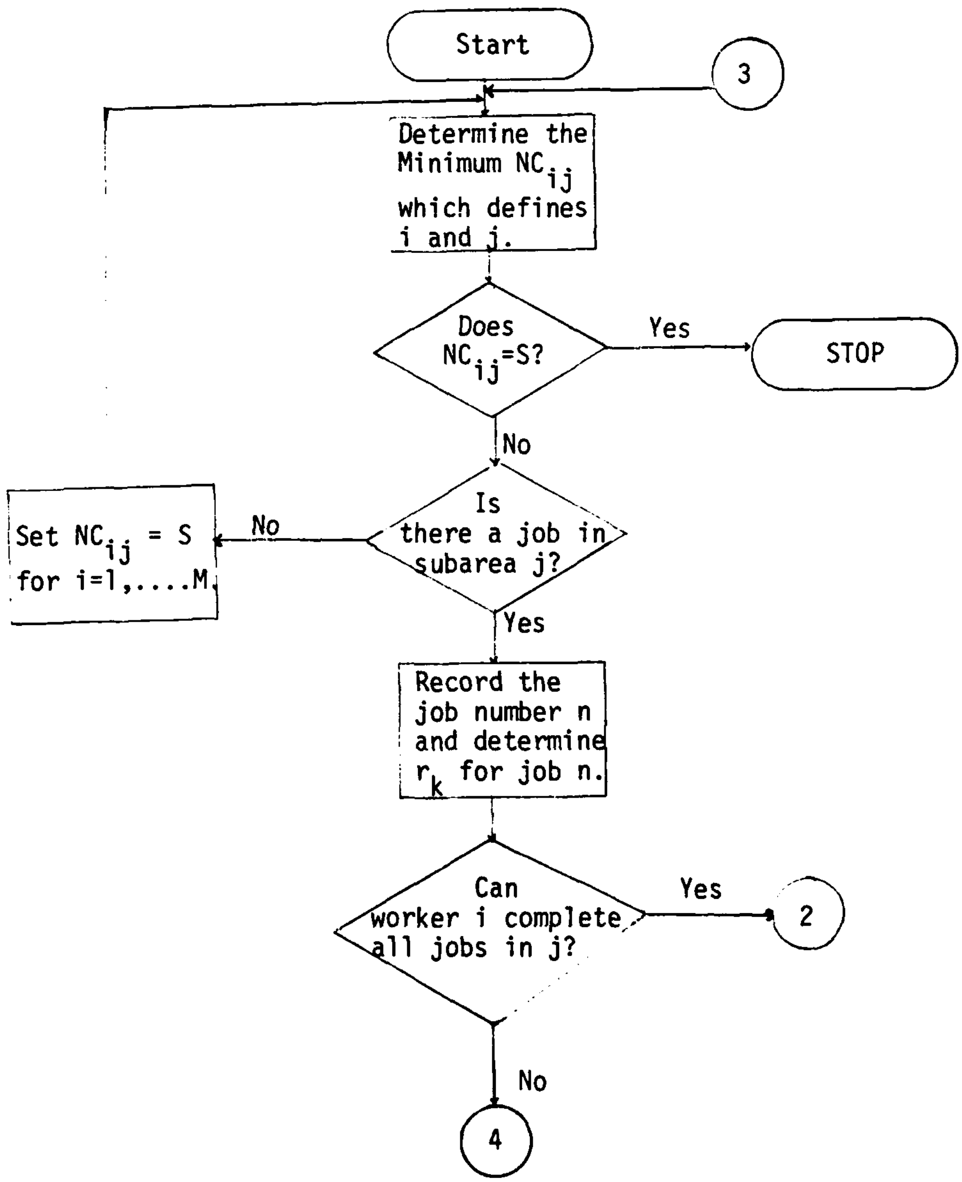


Illustration 4 Flowchart of Smallest Cost Method (Continued)

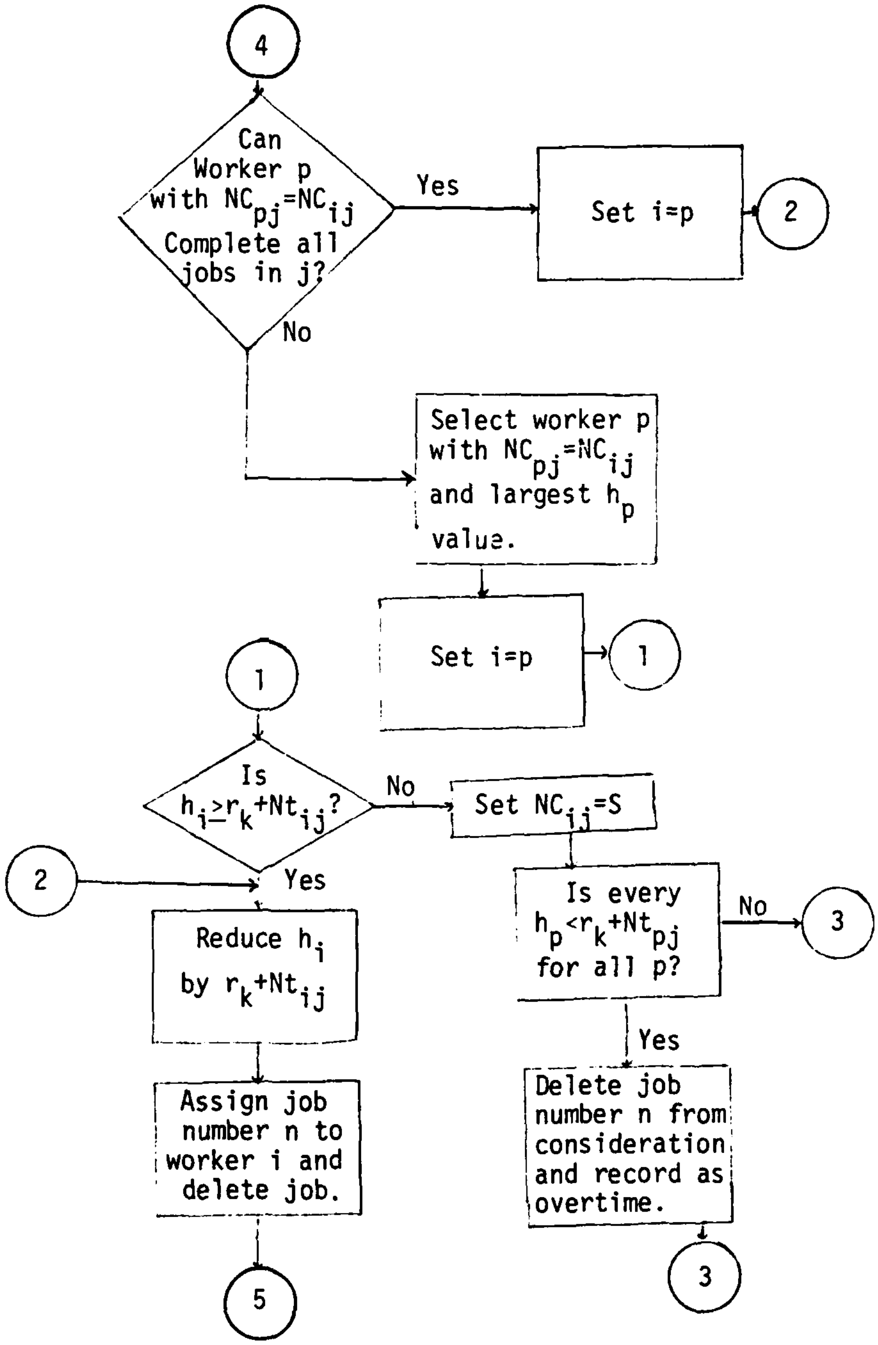


Illustration 4 Flowchart of Smallest Cost Method (Continued)

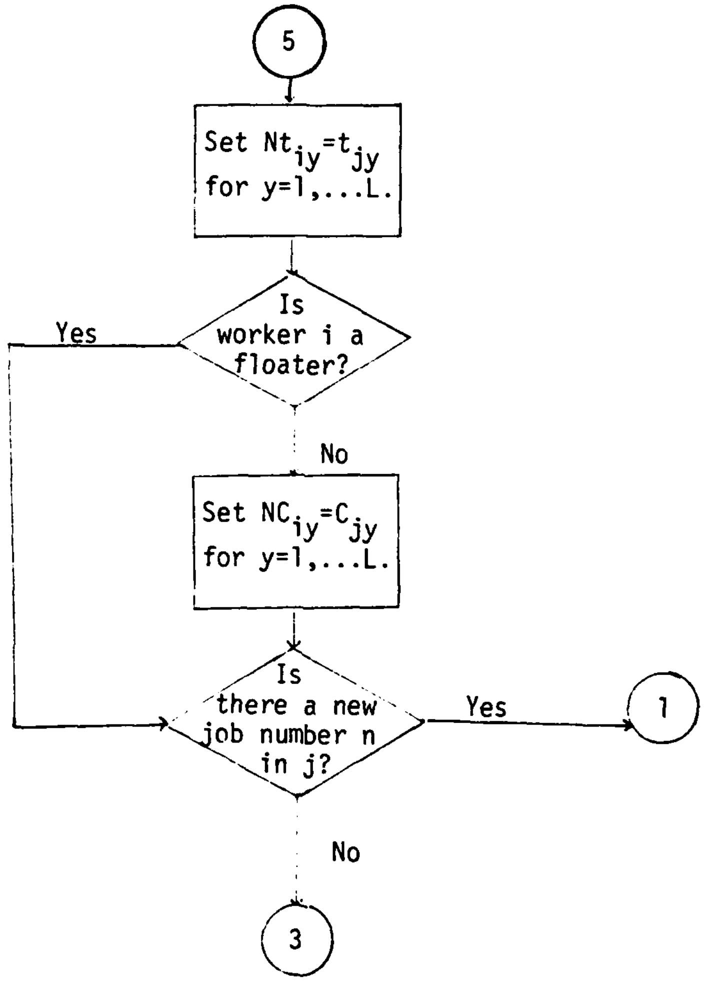


Table 7

Notation for Heuristics

i = Worker Number
j = Subarea Number
k = Job Type
L = Total Number of Subareas
M = Total Number of Workers
n = Job Number
S = A value larger than the maximum C_{ij} value
C_{ij} = Cost of worker i going to subarea j
NC_{ij} = Current cost of worker i going to subarea j
h_i = Hours worker i has available
t_{ij} = Travel time for worker i to subarea j
Nt_{ij} = Current travel time for worker i to subarea j
r_k = Standard work time for job type k

To solve this heuristic effectively a computer program was developed. This program is modularized by function with the main program doing all the input and output as well as some minor calculations. Subroutine SMLCST calculates the smallest NC_{ij} or does Step 1 in the heuristic and returns control to the main program. The main program then checks to see if the criteria for stopping in Step 2 is met. Subroutine FNDJOB is used to complete Step 3 of the heuristic by finding a job in the appropriate location if one exists and determing the appropriate work time value. If no job is found, FNDJOB eliminates that location from further consider-

ation, and the program returns to subroutine SMLCST. Subroutine WRKHRS is used to complete Steps 4, 5, 6, 7, in the heuristic. These steps all deal with the amount of time various workers with the same cost have to do a particular job. The subroutine attempts to select the best worker for the job based on the amount of time each has remaining and then updates his time once an assignment being made is imminent. This subroutine will also generate an overtime requirement if no worker is able to do the job. Assignments are made and stored for later output in subroutine ASSIGN. This subroutine completes Step 8 of the heuristic which includes deleting the job from consideration once it is assigned. Subroutine UPDATE can be accessed only from subroutine ASSIGN. This is only done when the worker's location on the previous job he was assigned is not the same as the job he was just assigned in ASSIGN. This means that the cost and travel time matrixes may need updated as outlined in Step 9 and 10 of the heuristic, and subroutine UPDATE accomplishes this. The program will continue to try to make assignments until the smallest cost value found in subroutine SMLCST is equal to a large value termed S. When this occurs, all possible jobs have been assigned, and the main program will cause summary reports to be generated. Essentially, three different reports are generated.

The first is a list of all jobs, the worker they are assigned to, and the location they are assigned in. The second report is the amount of time in hours that each worker has left for other assignments or duties. The last report is a cost estimate of how much it costs to do all jobs and perform all associated travel. The computer program is included as Appendix 5. This program is generalizeable for any day's jobs as long as the dimension statements and constants are entered correctly. User instructions are included as comment statements within the program itself. The program was designed to be easy to augment with additional subroutines if additional information is desired and for ease of implementation by the user.

In order to fully demonstrate how the heuristic operates, an example problem will be discussed next. For this example, there are three (3) workers who may go to two (2) distinct subareas. All workers are assigned to the same area with worker 1 assigned to subarea 1, worker 2 to subarea 2 and worker 3 is a floater. The S value for this example is 999, and the cost matrix is given below:

NC_{ij}/C_{ij} Matrix

Subarea j

		1	2
Worker i	1	0	113
	2	113	0
	3	112	112

For demonstration purposes, the number of hours each worker has available, h_i, will be limited as follows; worker 1 has 1.5 hours, worker 2 has 1.0 hours and worker 3 has .5 hours. Also, there will only be four (4) jobs to be scheduled. With adjusted work times in hours, those jobs are as follows:

Job Number(n)	Type(k)/Work Time(r_k)	Subarea(j)
1	1/.30	1
2	2/.45	1
3	4/.22	1
4	4/.22	2

The travel times for the workers to travel from their start points to the subareas are listed in the matrix below:

Nt_{ij}/t_{ij} Matrix (Hours)

Subarea j

		1	2
Worker i	1	.18	.25
	2	.25	.18
	3	.28	.27

With this information it is possible to determine a schedule of the jobs using the smallest cost method as follows:

1) The minimum $NC_{ij} = NC_{11} = 0$. i=1, j=1. (STEP 1)

2) The minimum $NC_{ij} \neq S$ or 999. (STEP 2)

3) Job #1 exists in subarea 1 and has an r_k value = .30. (STEP 3)

4) The total time to complete all jobs in subarea 1 by worker 1 is:

Job(n)	r_k		Nt_{ij}		
1	.30	+	.18	=	.48
2	.45	+	.18	=	.63
3	.22	+	.18	=	.40
					1.51 Hours - Total Time

No other worker's hours are sufficient to do all the jobs in subarea 1. (STEP 4)

5) $h_1 > h_2 > h_3$ therefore i=1. (STEP 5)

6) $h_1 \geq r_k + Nt_{ij}$ or $1.5 \geq .30 + .48$. (STEP 6)

7) $h_1 = 1.5 - (.30+.48) = .72$. (STEP 7)

8) Assign job #1 to worker 1. (STEP 8)

9) $Nt_{11}=.18$, $Nt_{12}=.25$, $NC_{11}=0$ and $NC_{12}=113$. (STEP 9)

10) Job #2 exists in subarea 1. (STEP 10)

11) $h_1 \geq r_k + Nt_{ij}$ or $.72 \geq .45 + .18$. (STEP 6)

12) $h_1 = .72 - (.45+.18) = .09$. (STEP 7)

13) Assign job #2 to worker 1. (STEP 8)

14) $Nt_{11}=.18$, $Nt_{12}=.25$, $NC_{11}=0$ and $NC_{12}=113$. (STEP 9)

15) Job #3 exists in subarea 1. (STEP 10)

16) $h_1 \ngeq r_k + Nt_{ij}$ or $.09 \ngeq .22 + .18$
therefore $NC_{11} = 999$.
$h_2 \geq r_k + Nt_{ij}$ or $1.0 \geq .40 + .25$. (STEP 6)

17) The minimum $NC_{ij}=NC_{22}=0$. $i=2$, $j=2$. (STEP 1)

18) The minimum $NC_{ij} \neq 999$. (STEP 2)

19) Job #4 exists in subarea 2 and has
an r_k value = .22. (STEP 3)

20) The total time to complete all jobs
in subarea 2 by worker 2 is:

Job(n)	r_k		Nt_{ij}		
4	.22	+	.18	=	.40 Hours - Total Time

$h_2 \geq r_k + Nt_{ij}$ or $1.0 \geq .40$. (STEP 4)

21) $h_2 = 1.0 - (.22+.18) = .60.$ (STEP 7)

22) Assign job #4 to worker 2. (STEP 8)

23) $Nt_{21}=.25$, $Nt_{22}=.18$, $NC_{21}=113$ and $NC_{22}=0$. (STEP 9)

24) No new job exists in subarea 2. (STEP 10)

25) The minimum $NC_{ij} = NC_{22} = 0$. i=2, j=2. (STEP 1)

26) The minimum $NC_{ij} \neq 999$. (STEP 2)

27) $NC_{i2} = 999$ for i=1, 2, 3. (STEP 3)

28) The minimum $NC_{ij}=NC_{31}=112$. i=3, j=1 (STEP 1)

29) The minimum $NC_{ij} \neq 999$. (STEP 2)

30) Job #3 exists in subarea 1 and has an r_k value = .30. (STEP 3)

31) The total time to complete all jobs in subarea 1 by worker 3 is:

Job(n)	r_k		Nt_{ij}		
3	.22	+	.28	=	.50 Hours - Total Time

$h_3 \geq r_k + Nt_{ij}$ or $h_3 \geq .50$. (STEP 4)

32) $h_3 = .50 - (.22+.23) = .00$ (STEP 7)

33) Assign job #3 to worker 3. (STEP 8)

34) $Nt_{31}=.18$, $Nt_{32}=.25$ and worker 3 is a floater. (STEP 9)

35) No new job exists in subarea 1. (STEP 10)

36) The minimum $NC_{ij}=NC_{31}=112$. i=3, j=1 (STEP 1)

37) The minimun $NC_{ij} \neq 999$. (STEP 2)

38) $NC_{i1} = 999$ for i=1, 2, 3. (STEP 3)

39) The minimum $NC_{ij} = NC_{11} = 999$. (STEP 1)

40) The minimum $NC_{ij} = 999$. STOP. (STEP 2)

At this point a solution to the problem has been generated. That solution is summarized as follows:

Worker(i)	Job Number (n)	Hours Remaining(h_i)
1	1, 2	.09
2	4	.60
3	3	.00

Possibly the most significant fact derived from this example problem, besides how the heuristic operates, is that the closest worker to a job may not be assigned to that job and an extra worker may be employed solely for the purpose of doing that job. In this example problem, worker 2 is closer to a job in subarea 1 than worker 3 as indicated by a travel time of .25 hours verses .28 hours. Yet worker 3 is considered for a job in subarea 1 first since worker 3 is a floater, and worker 2 is assigned to a subarea or location. This, of course, conforms to the rules that are to be followed for assignments, yet it is clear that worker 2 could get to subarea 1

faster than worker 3 and has enough time to do the work there, i.e., .60 is greater than .25 + .22. This illustrates that this method may generate solutions which are more costly than necessary for two reasons; larger travel times and extra workers being employed when not necessary. Yet, this is how the present system operates, and this method merely reflects that aspect.

In order to combat the two drawbacks mentioned for the first solution method, a second solution method was developed which completely relaxes the assignment rules followed under the present system. The projected gains from this are expected to be reduced cost through fewer workers being employed and/or travel times being reduced. Naturally, the expected problem is that the scheduling rules in existence may be violated on occasion. The concept for this method was derived from the closest-unvisited-city algorithm where the problem is to send a salesman to a number of different cities by the shortest overall route with each leg of the trip measured by time or distance. The algorithm works by selecting an arbitrary point of origin and has the salesman travel from there to the next closest city. This continues until all of the cities have been visited once. The problem to be solved is not a traveling salesman one yet the concept of always looking for the next closest

job site may be applicable. The second solution procedure assumes that it is and attempts to take advantage of it.

The second solution procedure is called the "closest-available-worker" method. The solution steps for the heuristic are almost the same as for the smallest cost method, but the criteria for selecting the next worker and subarea, or i, j pair to be considered is different. The selection criteria is to select the i, j pair which involves the smallest amount of travel time. In effect, this means the heuristic will attempt to make an assignment to the closest available worker to a given job when that job is considered. The job will be considered in a sequential fashion with other jobs in the subarea when the travel time for a worker to the location in which the job falls is the lowest value available. Again, no guarantee of optimality is made, yet, looking at the lowest travel times in a sequential fashion should allow for an efficient solution given that the assignment rules have been relaxed. Additionally, feasibility will be maintained by checking for it prior to making each assignment, and if the feasibility criteria is not met, then the assignment will not be made.

The heuristic procedure for this second solution method is essentially the same as for the smallest cost method, but two things

need to be changed. First of all, the cost or c_{ij} is now the travel time or t_{ij}. Second, no distinction is made between floaters and workers, and all are treated equally. These changes result in the 11 step procedure listed in Table 8. Aside from renumbering the steps, the only changes occur in Steps 1, 10, and 11.

Table 8

Closest-Available-Worker Method

(A Heuristic Procedure for Minimizing Travel Time)

STEP 1 Set $C_{ij} = t_{ij}$ and $NC_{ij} = Nt_{ij}$ where i=1, ...M and j=1, ...L.

STEP 2 Determine the minimum NC_{ij} where i=1, ...M and j=1, ...L. Then set i equal to the worker and j equal to the subarea associated with the minimum NC_{ij}.

STEP 3 If the minimum NC_{ij} = S, STOP.

STEP 4 For subarea j, determine if a job exists. If so, record the job as job number n and determine the standard work time for a job of its associated type k, i.e., r_k. If not set NC_{ij} = S for i=1,....M and go to STEP 2.

STEP 5 If worker i has enough hours available, h_i, to complete all the remaining jobs in subarea j, go to STEP 8. Otherwise, investigate all other workers who have an equal current cost value for subarea j to determine if

Table 8 Closest-Available-Worker Method (Continued)

any of them have enough hours available to complete all jobs in subarea j. For the first worker p who meets this requirement, set i=p and go to STEP 8.

STEP 6 Investigate all workers who have an equal current cost value for subarea j and select the worker p who has the most hours available, h_p. Set i=p.

STEP 7 If worker i's hours, h_i, are greater than or equal to $r_k + Nt_{ij}$ for job number n, go to STEP 8. Otherwise let $NC_{ij}=S$ and if every $h_p < r_k + Nt_{pj}$ for p=1, ...M, delete job number n from consideration and record it as an overtime requirement. Go to STEP 2.

STEP 8 Reduce h_i by $r_k + Nt_{ij}$.

STEP 9 Assign job number n to worker i in subarea j and delete job number n from consideration.

STEP 10 Set $NC_{iy} = C_{jy}$ and $Nt_{iy} = t_{jy}$ for y=1, ...L.

STEP 11 Determine if a new job number n exists in subarea j. If it does go to STEP 7. Otherwise go to STEP 2.

The same computer program that was used to solve the smallest cost heuristic is used to solve this heuristic with two modifications. The first one is made in the main program and merely involves adding a do-loop to set the C_{ij} values equal to the t_{ij}

values. The second modification is made in subroutine UPDATE. Removing the only if statement in this subroutine will cause all workers to be considered for jobs equally since the cost matrix will be updated for all workers as assignments are made. Appropriate comments have been placed within the computer program in Appendix 5 which will aid the user in making these modifications.

For comparison purposes the same example problem that was used to demonstrate the smallest cost heuristic will be used to demonstrate the closest-available-worker method. The solution steps are as follows:

1) $C_{ij} = t_{ij}$ and $NC_{ij} = Nt_{ij}$ for all i and j. (STEP 1)

2) The minimum $NC_{ij} = .18$. i=1, j=1. (STEP 2)

3) The minimum $NC_{ij} \neq 999$. (STEP 3)

4) Job #1 exists in subarea 1 and has an r_k value = .30. (STEP 4)

5) The total time to complete all jobs in subarea 1 by worker 1 is:

Job(n)	r_k		Nt_{ij}		
1	.30	+	.18	=	.48
2	.45	+	.18	=	.63
3	.22	+	.18	=	.40
					1.51 Hours - Total Time

No other worker's hours are sufficient to do all the jobs in subarea 1. (STEP 5)

6) $h_1 > h_2 > h_3$ therefore i=1. (STEP 6)

7) $h_1 \geq r_k + Nt_{ij}$ or $1.5 \geq .30 + .48$. (STEP 7)

8) $h_1 = 1.5 - (.30+.48) = .72$. (STEP 8)

9) Assign job #1 to worker 1. (STEP 9)

10) $Nt_{11}=.18$, $Nt_{12}=.25$, $NC_{11}=.18$ and $NC_{12}=.25$. (STEP 10)

11) Job #2 exists in subarea 1. (STEP 11)

12) $h_1 \geq r_k + Nt_{ij}$ or $.72 \geq .45 + .18$. (STEP 7)

13) $h_1 \geq .72 - (.45+.18) = .09$. (STEP 8)

14) Assign job #2 to worker 1. (STEP 9)

15) $Nt_{11}=.18$, $Nt_{12}=.25$, $NC_{11}=.18$ and $NC_{12}=.25$. (STEP 10)

16) Job #3 exists in subarea 1. (STEP 11)

17) $h_1 \not\geq r_k+Nt_{ij}$ or $.09 \not\geq .22 + .18$ therefore $NC_{11} = 999$. $h_2 \geq r_k + Nt_{21}$ or $1.0 \geq .40 + .25$ (STEP 7)

18) The minimum $NC_{ij} = NC_{22} = .18$. i=2, j=2 (STEP 2)

19) The minimum $NC_{ij} \neq 999$. (STEP 3)

20) Job #4 exists in subarea 2 and has an r_k value = .22. (STEP 4)

21) The total time to complete all jobs in subarea 2 for worker 2 is:

Job(n)	r_k	Nt_{ij}
4	.22 +	.18 = .40 Hours - Total Time

$h_2 \geq r_k + Nt_{ij}$ or $1.0 \geq .40$. (STEP 5)

22) $h_2 = 1.0 - (.22+.18) = .60$. (STEP 8)

23) Assign job #4 to worker 2. (STEP 9)

24) $Nt_{21}=.25$, $Nt_{22}=.18$, $NC_{21}=.25$, $NC_{22}=.18$. (STEP 10)

25) No new job exists in subarea 2. (STEP 11)

26) The minimum $NC_{ij} = NC_{22} = .18$. i=2, j=2. (STEP 2)

27) The minimum $NC_{ij} \neq 999$. (STEP 3)

28) $NC_{i2} = 999$ for i=1, 2, 3. (STEP 4)

29) The minimum $NC_{ij} = NC_{21} = .25$. i=2, j=1. (STEP 2)

30) The minimun $NC_{ij} \neq 999$. (STEP 3)

31) Job #3 exists in subarea 1 and has an r_k value = .30. (STEP 4)

32) The total time to complete all jobs in subarea 1 by worker 2 is:

Job(n)	r_k	Nt_{ij}
3	.22 +	.28 = .50 Hours - Total Time

$h_2 \geq r_k + Nt_{ij}$ or $.60 \geq .50$. (STEP 5)

33) $h_2 = .60 - (.22+.28) = .10$. (STEP 8)

34) Assign job #3 to worker 2. (STEP 9)

35) Nt_{21}=.18, Nt_{22}=.25, NC_{21}=.18 and NC_{22}=.25. (STEP 10)

36) No new job exists in subarea 2. (STEP 11)

37) The minimum $NC_{ij} = NC_{21} = .18$. $i=2$, $j=1$. (STEP 2)

38) The minimum $NC_{ij} \neq 999$. (STEP 3)

39) $NC_{i1} = 999$ for i=1, 2, 3. (STEP 4)

40) The minimum $NC_{ij} = NC_{11} = 999$. (STEP 2)

41) The minimum $NC_{ij} = 999$. STOP. (STEP 3)

At this point a solution to the problem has been produced. That solution can be summarized as follows:

Worker(i)	Job Number(n)	Hours Remaining(h_i)
1	1, 2	.09
2	3, 4	.10
3	-	.50

While the solution procedure for the closest-available-worker method seemingly procedes in the same manner as the smallest cost method, important differences in the solutions result. In this case, job #3 is not assigned to the floater, worker 3, as it was previously but to worker 2 who happens to be closer to the job site but is also assigned to subarea 2. Obviously, the assignment rules have been violated for the job, but it should be noted that

they were not violated when the other three jobs were assigned. Possibly, the most critical thing to note is whether or not the heuristic employed the workers more efficiently than in the first case. Firstly, it used one less worker since it left worker 3 unassigned which is more efficient. Secondly, it had the added benefit of reducing overall travel time. By assigning worker 2 to job 3 instead of worker 3, travel time to that job was reduced from .28 to .25 and remained the same for the remainder of the jobs. This illustrates that this method was able to combat the two problem areas encountered with the smallest cost method, yet, it was only able to do this by violating one of the assignment rules.

In this chapter two solution methods to the problem have been developed. The first is the smallest cost method and attempts to ke assignments that are compatible with the rules that have been established. These rules may cause the assignments to be more expensive than necessary. Therefore, a second heuristic procedure was developed in order to try to reduce expense by relaxing the assignment rules. This procedure is called the closest-available-worker method and is based on the travel times for the workers to go from their location to the job's location. Illustrations were given of both methods and in these illustrations both the methods

performed as desired. In the next chapter, these methods will be tested more stringently to see if they perform as desired in a real situation.

CHAPTER IV

EXPERIMENTAL ANALYSIS

This chapter analyzes how well the two heuristic methods perform with respect to the present method of allowing the foremen to make the assignments on their own. First an appropriate historical period is selected so that data can be obtained for model validation. Second a cost equation is developed and all methods compared using this cost equation. Last the actual assignments that were made are compared with what assignments would have been made using the two heuristic methods. Gathering historical data and validating a model using it has two disadvantages. First, it is usually difficult to make any statistical tests using this method. Second, since these data are historical, they are based on some past actions, and these actions might have been changed had the model been in existence. Nonetheless, this method is the most viable method to use in testing these two models since quantitative measures can be devised to measure the cost of the assignments, and they can be compared to assignments that were made using the present method of letting the foreman make all assignments. Also, it is not possible to use the models to make assignments at this time since it has not yet been accepted by

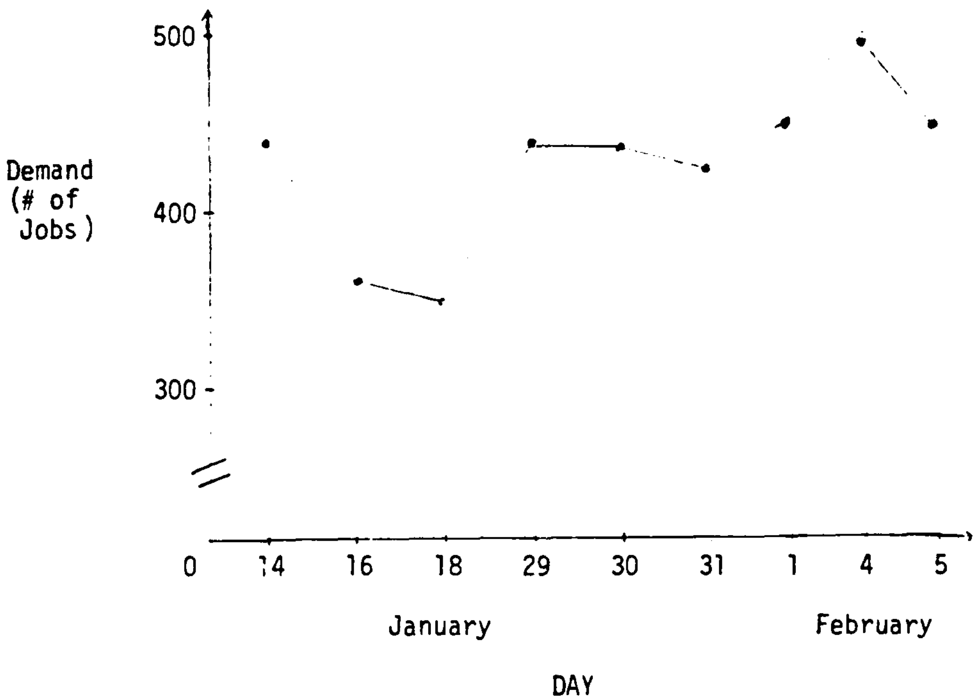
the company involved; therefore, historical data are the best available. The data to be used were selected to meet two criteria which are currency and rigor. The inclusion of currency indicates the desirability of obtaining data that are as recent as possible. Therefore, the months of January and February 1980 were selected since that is the timeframe the experimentation is being done. The criterion of rigor is met by obtaining data that will test the model under as many different situations as possible. This can be done by selecting the data so that they fall within three different timeframes. These timeframes are the middle of the month, the end of the month and the first of the month. This will result in covering the periods of the month in which demand is at its peak which is near the beginning of the month, and when it is low, which is near the middle of the month. This fluctuation is due primarily to two factors. The first is pay periods. Many people are paid the 1st of the month, and some are paid on the 15th. This normally causes highest demand close to these dates as people can pay their bills and, therefore, request turn on or transfer service. The second factor is leases which normally run to the 1st of the month. This causes a greater demand for transfer of service on or about this time. These fluctuations also cause the mixture of job types to

change since the demand for type 1 jobs is greater near the 1st of the month and less during other periods. This means that if the data are selected to cover all these periods, a fairly rigorous test will have been completed. Therefore, the following test dates were selected: 14, 16, 18, 29, 30, and 31 January and 1, 4, and 5 February. Two and 3 February are a Saturday and Sunday, and so no work was scheduled on those days. A graph of the demand versus day bears out the assumptions that were made with respect to demand. This graph is included as Illustration 5. The peak demand of 493 jobs occurred on 4 February which was the first full work day after payday and the minimum demand of 350 jobs on 18 January which was a Friday during the middle of the month. The total number of jobs over the period is 3,848 with an average day having 428 jobs. By looking at this large a number of jobs, the confidence in the experimental results should be relatively high.

With the historical period to be evaluated known, it is possible to outline the specific procedure for evaluating each of the solution methods. It involves scheduling the jobs for each day using each of the methods and then comparing them against a standard. Since the optimum schedule remains unknown, the test standard will be the schedule the foreman made up for that day. This information is available

Illustration 5

Demand Versus Day for the Experimental Period



on the dispatcher's route list which includes all the items of information necessary for input to exercise the models. These items include the number of hours each worker has available for the day, h_i, the job type, k, the location of the job, j, and which worker, i, was assigned to job number, n. Naturally, the information was not in this format but had to be interpreted from the dispatcher's handwritten records. The means of comparison will be both a cost analysis and an assignment analysis. Cost analysis will include the vehicle cost and labor cost. Assignment analysis will involve investigating where the differences in assignments are and an evaluation of how reasonable these differences seem to be.

Cost analysis will be completed first and the notation used is defined in Table 9. Before proceding, each parameter used to determine the total cost equation will be discussed individually and the way they can be calculated outlined. The variable TD is the total distance that the workers drive to complete all the jobs for the day. This can be calculated by multiplying the straight line distances, d_{ij}, in miles by 1.22 to convert them to over-the-road distances then summing up the distance traveled by each worker to and within each subarea.

Table 9

Notation for the Cost Analysis

TC = The total cost of assignments in dollars.
TD = The total distance traveled by all vehicles.
VC = The vehicle operating cost per mile.
FH = The total number of hours all foremen have available.
FR = The foremen's pay rate per hour.
WH = The total number of hours all workers have available.
WR = The worker's pay rate per hour.
SV = The total savings.
FD = The total number of hours recovered from all foremen.
WD = The total number of hours recovered from all workers.
f_i = Hours saved from floater i in a given day.

The variable VC, the vehicle operating cost per mile, is a combination of different costs. The first is a maintenance cost which is prorated on a mileage basis. The second is a depreciation cost which prorates the purchase cost on a mileage basis, and the third is a fuel cost based on the number of miles per gallon that the fleet of vehicles averages. The estimate for this cost is .25 dollars per mile driven. Naturally, as interest rates increase and the cost of fuel increases, this figure will become larger, and, therefore, more and more significant to the cost equation. The total number of hours that the foremen have available, FH, is a

constant figure which estimates how much time it takes all the foremen to make out their schedules under the present system. A good estimate of this is one hour per day for each foreman or a total of three hours per day.

The variable FD, the total number of hours recovered from all foremen, is the amount of time either the smallest cost or the closest-available-worker method will save the foremen. For the present method the FD equals 0 since no time will be saved. In other words, it is the amount of time the foremen will be able to spend doing some other useful task rather than scheduling if one of the alternative methods is implemented. It is expected that a 50% savings would result after implementation or FD = .50 FH for one of the alternative methods. FR, the foremen's pay rate per hour, is a constant and is $11.00 per hour. The total number of hours all workers have available, WH, is a variable number which depends on how much absentee time each worker requests for a day and how many workers are scheduled to work. This figure is the h_i value prior to any work being done. The worker pay rate per hour, WR is a constant and is $9.41 per hour for all workers.

The variable WD, the total number of hours recovered from all workers, only applies to floaters since these employees are the only

workers that are eligible to be assigned to other duties or deleted through attrition. The company estimates that for any floater having 3.5 hours or more available in a given day to do other tasks, other worthwhile tasks can and will be found. Additionally, if this condition persists over an extended period of time, the worker's position can be terminated or structurally reassigned. The variable SV, the total savings is a combination of the salary saved through the hours recovered from the foremen, FD, and from the workers, WD. These savings will occur only if the time saved is actually employed usefully or the savings results in an overall work force reduction.

At this point, it is possible to state an equation for the total cost of doing the assignments for a given day which is denoted TC. Therefore:

$$TC = (TD \cdot VC) + (WH \cdot WR) + (FH \cdot FR) - SV$$

Where:

$$SV = (WD \cdot WR) + (FD \cdot FR)$$

In essence, this equation states that total cost is the sum of four terms. The first, $TD \cdot VC$, is the cost relating to operating the vehicle in conjuction with doing the jobs. The $FH \cdot FR$ term, is the cost of having the foremen do the assignment process without

assistance. The WH·WR term, is the total salary that must be paid to the workers for being available to perform jobs. Lastly, SV is a measure of savings that may be derived by either saving the foremen's time or the worker's time.

In order to use the equation for total cost, it is necessary to produce computational formulas.

A) Since:

$$TC = (TD \cdot VC) + (WH \cdot WR) + (FH \cdot FR) - SV$$

Where:

$$SV = (WD \cdot WR) + (FD \cdot FR)$$

B) By substitution of SV:

$$TC = (TD \cdot VC) + (WH \cdot WR) + (FH \cdot FR) - (WD \cdot WR) - (FD \cdot FR)$$

C) By consolidating terms:

$$TC = (TD \cdot VC) + ((WH - WD) \cdot WR) + ((FH - FD) \cdot FR)$$

D) Let f_i represent the hours saved from floater i in a given day.

Then by substituting constant values and known parameters:

1. TC (present method) =

$$(.25 \cdot TD) + (9.41 \cdot (\sum_{i=1}^{M} h_i - \sum_{i=1}^{M} f_i)) + 33.00$$

2. TC (new methods) =

$$(.25 \cdot TD) + (9.41 \cdot (\sum_{i=1}^{M} h_i - \sum_{i=1}^{M} f_i)) + 16.50$$

Equations 1 and 2 are the computational formulas used to do the cost analysis.

Important to note is the differences that may exist between the latter two equations term by term. These differences are areas where cost reductions are possible; therefore, they are the critical aspects of the equations. In the first term, the .25 is a constant for both equations and the TD value may change between the two equations. Therefore, a cost reduction may occur if the total distance traveled to perform all jobs is reduced which is a logical and desirable consequence. In the second term, the variable which may differentiate cost between equations 1 and 2 is the number of floaters who have more than 3.5 hours remaining after they have completed their jobs. The more hours these floaterspossess, the lower the cost. This is also desirable because these hours can be put to use elsewhere and do in fact constitute a savings. The third term is a constant term which merely reflects a 50% reduction in cost for foremen if one of the heuristics is employed versus the present manual system. This was designed to be a conservative estimate of the cost savings which does not include the foremen's overhead costs, but neither does it include the additional computational expenses of the computerized heuristic. It can be concluded that, in order to show a cost differential between the two methods larger than the difference between the two constant values in equations 1

and 2 or $16.50, either the overall distance traveled must be reduced or the number of hours which can be diverted must be increased or both. For this problem, both these conditions are desirable which is an indication that the cost equation is a valuable tool for comparision among the models. In addition, this indicates that the cost equation is only sensitive to the distance traveled by the workers and the floater hours. Since the distances involved are relatively short and are evaluated at $.25 per mile, this component will have less impact on the overall equation than saving floater hours since they cost $9.41 each. This would result in a large increase in the amount of distance traveled being overshadowed by a decrease in the number of hours the floaters work. From a cost standpoint, this may still be desirable but from a political and energy conservation perspective, it may not be acceptable. Therefore, it may be necessary to investigate each of these cost items more closely.

Each of the three methods of assignment was evaluated for each of the nine days, and both of the heuristic procedures produced lower total costs, TC, than the present procedure of the foreman doing the assignments alone. The computational results are listed in Table 10.

Table 10

Total Cost Evaluation for Both Heuristic Methods

DATE	PRESENT	SMALLEST COST	CLOSEST-AVAILABLE WORKER
14 January	$ 2,919.53	$ 2,778.05	$ 2,459.01
16 January	2,590.05	2,447.69	2,162.54
18 January	2,442.77	2,331.17	2,126.83
29 January	2,782.10	2,585.02	2,388.65
30 January	2,735.70	2,623.52	2,377.57
31 January	2,709.31	2,540.87	2,336.68
01 February	2,705.29	2,585.92	2,476.53
04 February	3,112.40	2,884.26	2,740.57
05 February	2,719.71	2,638.98	2,436.33
TOTAL	$24,716.86	$23,415.48	$21,504.71
% Savings	—	5.26	13.00

In every case both heuristics performed better than the present method. The performance of the smallest cost method ranged between a 2.97% savings and a 7.33% savings with an expected savings of 5.26%. This is quite good considering that the method followed the same rules as the foremen. The closest-available-worker method out-per-

formed both the other methods but was not constrained by the assignment rules. The savings ranged between 8.46% and 16.51% with an expected value of 13.00%. If this method were implemented and achieved the expected value, the savings for one year would be approximately $90,000. Also, the travel time and distance was reduced for all nine days using the smallest cost method and in seven out of nine days for the closest-available-worker method. The two days where travel was not reduced were 30 January and 01 February, and the cost increases were $16.79 and $9.72 respectively. This increase was caused by each worker involved having to travel to more locations as a result of a reduced work force from the present system. Since it occured only two times and for relatively small amounts versus the overall cost savings on those days, travel distance increases do not appear to be a problem in either of the two methods. In fact, in sixteen (16) out of eighteen (18) trials, they were reduced. However, the major portion of the cost reductions can be attributed to a reduction in the number of workers required to be present to make the system operate.

From purely a cost standpoint the closest-available-worker method is the most desirable yet one other factor must be analyzed before this conclusion can be drawn. That factor relates to the

quality of the assignments which involves such items as whether or not the assignment rules that presently exist are being followed and if the changes are reasonable ones. The key work here is "changes". It is not necessary to debate each and every job for all 3,848 jobs but rather to analyze the jobs which the models assign differently from the foremen. In order to make this comparison, it is preferable to look at each day individually and compare the assignments made by one of the heuristics with the actual assignments made by the foremen.

First a comparison will be made between the assignments made by the smallest cost method and the present method. The smallest cost method attempts to follow the same rules as the present method and improve worker utilization where possible. This should cause the assignments to be relatively similar. A summary of the differences between jobs assigned to floaters and those assigned to workers is contained in Table 11. Only 5.8% of the total number of jobs are assigned differently using the smallest cost method and none of the assignment rules are violated on any of the nine days. The method tends to assign an additional job to a worker assigned to a subarea rather than distribute the jobs more evenly between the workers and floaters. This makes sense because the foremen are interested in keeping all the men that they are given for the day, therefore would

Table 11

Smallest Cost Assignment Comparison

DATE	# OF JOBS ASSIGNED DIFFERENTLY	% OF TOTAL JOBS ASSIGNED DIFFERENTLY	WHERE JOBS REASSIGNED FLOATERS	WORKERS
14 January	30	6.8	10	20
16 January	32	8.7	8	24
18 January	15	4.3	4	11
29 January	27	6.1	3	24
30 January	22	5.0	1	21
31 January	16	3.8	4	12
01 February	22	4.9	6	16
04 February	37	7.5	13	24
05 February	22	4.9	15	7
TOTAL	223		64	159

distribute the workload more evenly in order to keep all workers occupied. While the model attempts to get the most possible out of all workers so that the ones that are not needed can be reassigned elsewhere. One other thing is implied by the similarity between the assignments made by the smallest cost method and those made by the foremen. This similarity indicates that the model is a rather accurate portrayal of the real world since only minor explainable

differences exist. This is important both from a feasibility standpoint and implementability. Feasibility is indicated because the assignments are being accomplished under the present system so if the model only makes minor changes then its feasibility is also implied. Implementability is indicated because very little resistance should be encountered to a system that essentially maintains the status quo but at a reduced cost and with more information for management.

Next a comparison will be made between the assignments made by the closest-available-worker method and the present method. Since the closest-available-worker method makes no attempt to follow the present assignment rules, the most important aspect is to determine just how many times these rules are actually violated. If the number of violations is low, it may be possible to implement this method in order to reap the benefits of higher savings. On the other hand, if there is a larger number of violations, then the solution will not be practical. The applicable numbers are reflected in Table 12. Floaters were considered to be part of a pool who were free to be assigned in any area initially but once assigned then the rules were checked for compliance from that point on. Two types of violations occur and they are when workers assigned a sub-

Table 12

Closest-Available-Worker Assignment Comparison

DATE	NUMBER OF VIOLATIONS	PERCENT OF VIOLATIONS	WORKER VIOLATIONS	FLOATER VIOLATIONS
14 January	42	9.5	42	—
16 January	54	14.9	48	6
18 January	30	8.6	30	—
29 January	29	6.6	28	1
30 January	39	8.9	29	10
31 January	41	9.7	35	6
01 February	31	6.9	29	2
04 February	25	5.1	21	4
05 February	27	6.0	24	3
TOTAL	318		286	32

area are assigned to a job outside of that subarea when floaters are still available, or floaters are assigned outside their area while floaters are still available who could be assigned to that area. In Table 12, the former violations are termed worker violations and the latter are called floater violations. The percentage of violations for all jobs is 8.3% with the vast majority of these being of the worker type. These violations usually occur because a worker assigned to a subarea has additional time available

after completing all jobs within his subarea and is then assigned to an adjacent subarea to provide assistance. Obviously this is of more use to the company than the worker just being paid for doing nothing and the company having to pay to send a floater out to perform this work. Thus, a significant cost savings, can be realized by applying this method if an 8% rule violation is acceptable or can be made acceptable.

One additional benefit is gained from this method and that is that often whole workers remain unassigned which is of benefit since it is easier to reassign or delete a worker with a whole day available rather than two workers with half days each. The cost equations would consider these two items equivalent since in each case there is one whole day available yet most managers would prefer the option with the one worker with a full day merely due to ease of control and redeployment. For the nine days tested, the closest-available-worker method would leave these numbers of workers completely unassigned: 4, 5, 2, 6, 6, 6, 7, 6, and 5. The closest-available-worker method would make these workers blatantly available to the system's manager for other uses if the assignment rules could be bent. Naturally, the foremen never left a worker unassigned, and the smallest cost method left the following number unassigned: 0, 0,

0, 2, 1, 0, 2, 1, and 0. Clearly, the closest-available-worker method with 57 unassigned workers over the nine day test is superior.

In this chapter, the results of a large experiment covering nine days and close to 4,000 jobs was discussed. Both solution methods were used to determine the number of jobs of a specific type and location that each worker would be assigned. The results of these methods were compared against assignments actually made by the foremen on the days in question. Both methods were able to outperform the foremen in terms of cost, but the closest-available-worker method was clearly superior. Yet, it must be remembered that the assignment rules were not taken into account by this method and when the actual assignments were analyzed approximately 8% of the jobs were in violation of the rules. On the other hand, the smallest cost method did not violate any of the rules and was still able to achieve a 5.26% savings by assigning 5.8% of the jobs differently than the foremen actually did.

CHAPTER V

RECOMMENDATIONS AND CONCLUSION

This chapter recommends which heuristic should be implemented and how it should be done. Then possible extensions for the model and future work are discussed prior to the conclusion of the thesis. The recommendation is that the smallest cost model be implemented by Columbia Gas at the earliest practical date. This model was chosen because it was able to meet all of the objectives outlined for a successful model. First the model is able to use the data that are presently available on the computer system plus some cost, travel and distance data to make assignments with computer run times in the neighborhood of 10 seconds. This low run time will allow the manager to run the model a number of times for a single day to observe the effect of varying the size of the work force or doing additional jobs. Second, this model will be able to generate a schedule for the next day almost as soon as the telephone operators accept the last call for work the day before. The cutoff time for accepting jobs will be around 3:00 p.m. which means the manager will have between 3:00 p.m. and 6:00 p.m. to analyze the output which will consist of the assignments for all

workers, an estimate of the number of hours each worker will have available and a cost estimate for completing all the jobs for the next day. This lead time will allow the manager to plan ahead for the next day rather than just react during the day to problems that arise and also enable him to make any experimental runs he desires. Third, this method will improve the overall efficiency of the scheduling system. It is estimated that foremen will only have to spend half as much time on their scheduling duties. A 5.26% savings on man hours and travel costs can be expected when this method is implemented with realistic assignments being made. In fact, only 5.8% of the total number of jobs would be assigned differently than they would have been if assigned by the foremen alone. The differences are the result of attempting to get each worker to perform up to his capabilities rather than spreading the workload around so that everyone is occupied for at least part of the work day. These differences do not result in any violations of the present assignment rules which should aid in preserving the tranquility between workers and management while still employing the individuals involved more efficiently. This solution method has one more advantage. It can be implemented as a first step, and when it has been operating for a reasonable period of time, the closest-available-worker method

can be implemented to reduce costs even further if desired. This would be possible due to the close relationship between the methods employed by both heuristics and would essentially only involve changing the decision criteria from cost to travel time. This two step procedure would lessen the initial shock to the workers, thereby helping to keep their overall morale good, and lessening the probability of a strike or of unionization due to the violations of the assignment rules which are inherent in the closest-available-worker heuristic.

Implementaion of the smallest cost model should be accomplished in parallel with the present system. For a two week period both the present system and the new system should make assignments and the results compared. Any last minute adjustments to the model should be made at this time. For example, it may be determined through discussions with the foremen that the intra-area travel time for one subarea is too high. This time can then be adjusted accordingly prior to actually making assignments with the new model. As much input as possible should be acquired and encouraged from both the foremen and the manager of the system during this trial period. This will give them a vested interest in the success of the system which will help in making it a success. During this

period, the manager and the foremen should be well trained in manipulation of the model and how to interpret the output. This model was not designed to be blindly followed, but rather as a decision aid which should be changed and manipulated as necessary. Once the first two week test period is complete and events are proceding satisfactorily, all assignments should be made with the new model and assignments critiqued by the manager and formen with appropriate adjustments made. For example, it may be realized that a specific worker is quite slow in performing his tasks in relation to the standard work times. If the decision of the manager, is to keep the employee with the firm and make the necessary adjustments, the actual hours that the employee has available may have to be reduced by a constant factor in order to compensate. Eventually, this model should be integrated into an overall management information system oriented toward providing the manger with useful information that will allow him to plan and manage rather than just react to crises as they occur. The implementation of this model should be viewed as a first step in the implementation of a comprehensive management information system.

One obvious extension of this model is to use it in other cities serviced by Columbia Gas. Less obvious perhaps is for other utility

companies with standard repair jobs and assigned work areas to employ the methodology for their servicemen. Applications for this model may be found with telephone repairmen, electric meter repairmen and possibly water company meter repairmen. With minor modifications, many of these individuals may fall within the useful range of the model after the model's parameters were adjusted for their use. The two most critical adjustments would occur in the cost parameter and the work time parameter. The cost parameter is based on following certain assignment rules in the smallest cost method which may or may not be applicable for Columbia Gas in a unionized city or for another utility. The work time parameter is successful in this case because the jobs being performed are homogeneous, and the time to complete them is quite predictable. If the jobs do not fall into this category, but have a large variance involved in them by their nature then some type of probabilistic model would be necessary to generate these work times, and this heuristic algorithm may be inappropriate. Nonetheless, several reasonable extensions for this useful model do exist with the most appropriate being for service centers in other cities where Columbia Gas has accounts such as Pittsburgh, Pennsylvania, or Wheeling, West Virginia.

There are also several areas available for future work within the general scope of this problem. The first would be to develop a practical integer nonlinear program that would solve the mathematical formulation of the problem optimally. This could either be done for purely theoretical reasons, or it could be applied to this problem specifically. If it were applied, the total run time for the program would have to be in the neighborhood of one minute or less in order to be cost effective. If it were not, the application would be extremely limited in a low budget assignment area such as this. The second area would fall into the category of forecasting. In order to properly staff a service center, a good estimate of the services to be performed on a daily, monthly and yearly basis needs to be developed. At this time, no model exists to do this for the service center manager and staffing is based mainly on the total number of accounts for which the service center or service area is responsible. A forecasting model would be useful for the manager to appropriately distribute his assets. Specifically it would be useful in predicting the correct number of assets to have on hand for a given day in order to be able to complete the expected workload, and the scheduling model would then distribute these assets appropriately.

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A HEURISTIC MODEL FOR SCHEDULING REPAIRMEN TO JOBS USING DETERM--ETC(U)

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The last area where future work may exist is in the area of management information systems. Utilities are just now realizing that they can use their own or leased computer facilities to do more than just the accounting functions. These utilities are in need of analysis being done on what decision aids and other information managers need to operate effectively. Also, the design of computer based information systems to provide the information is critical. The design of such a system to support a service center would be both challenging and useful. With the increased cost consciousness of the public utilities due to increasing energy costs, lucrative and challenging applications of operations research techniques will continue to increase.

In conclusion, a model has been successfully developed which will do the scheduling of repairmen to jobs for one utility company. As long as the assumptions surrounding the use of the deterministic parameters involved are met, this heuristic model can have some applications in the field of public utilities. But in each application the methodology will undoubtedly have to be modified, and the success of the application will depend on how appropriate those modifications are.

APPENDIX 1

Straight Line Map Distance (Millimeters) Subarea (j)

Number (i) d_{ij}(mm)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	113	60	80	140	182	280	225	312	275	199	162	254	369	382
2	113	0	172	48	246	153	285	303	232	167	87	73	148	257	302
3	60	172	0	134	81	104	281	186	354	330	259	221	314	431	435
4	80	48	134	0	204	106	250	255	237	197	130	118	194	300	350
5	140	246	81	204	0	132	276	129	402	397	333	300	393	505	513
6	182	153	104	106	132	0	180	152	269	275	230	224	298	391	454
7	280	285	281	250	276	180	0	191	232	316	327	356	397	444	577
8	225	303	186	255	129	152	191	0	380	416	382	373	450	538	607
9	312	232	354	237	402	269	232	380	0	129	200	268	246	238	432
10	275	167	330	197	397	275	316	416	129	0	96	169	120	128	304
11	199	87	259	130	333	230	327	382	200	96	0	73	71	170	253
12	162	73	221	118	300	224	357	373	268	169	73	0	97	222	230
13	254	148	314	194	393	298	397	450	246	120	71	97	0	128	189
14	369	257	431	300	505	391	444	538	238	128	170	222	128	0	238
15	382	302	435	350	513	454	577	607	432	304	253	230	189	238	0
16	272	224	322	262	402	360	510	497	413	295	213	157	179	284	128
17	220	185	267	218	348	312	467	447	393	283	193	126	177	296	178
18	207	137	261	181	343	283	424	430	327	215	127	68	110	234	172
19	251	156	308	176	368	242	271	278	95	46	108	177	152	173	340
20	78	72	134	79	215	163	325	300	301	234	145	90	187	310	300
21	105	70	162	93	244	187	342	328	300	220	127	65	162	288	273
22	142	99	196	130	278	225	379	377	320	227	132	59	149	277	237
23	172	140	221	170	300	263	420	397	358	258	164	91	166	292	215
24	184	163	230	191	309	279	440	411	382	282	187	115	186	310	214
25	198	183	239	209	316	294	459	423	403	302	207	136	204	327	215
26	150	146	192	161	270	247	413	374	283	188	116	200	327	251	130
27	116	133	156	142	234	215	385	339	365	284	190	121	213	341	284
28	49	90	102	80	183	143	315	273	315	256	171	122	218	338	332
29	86	139	118	133	192	187	363	300	368	301	210	148	244	369	326
30	140	200	164	199	229	249	428	348	431	356	261	192	283	410	325
31 - 52	118	35	170	70	250	174	317	322	264	187	97	52	143	263	279

Number (i) d_{ij}(mm)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	272	220	207	251	78	105	142	172	184	198	150	116	49	86	140
2	224	185	137	156	72	70	99	140	163	183	146	133	90	139	200
3	322	267	261	308	134	162	196	221	230	239	192	156	102	118	164
4	262	218	191	176	79	93	120	170	191	209	161	142	80	133	199
5	402	348	343	368	215	244	278	300	309	316	270	234	183	192	229
6	360	312	283	242	163	187	225	263	279	294	247	215	143	187	249
7	510	467	424	271	325	342	379	420	440	459	413	385	315	363	428
8	497	448	430	278	300	328	366	397	411	423	374	339	273	300	348
9	413	393	327	95	301	300	320	258	382	403	373	365	315	368	431
10	295	283	215	46	234	220	227	258	282	302	283	284	256	301	356
11	213	193	127	108	145	127	132	164	187	207	188	190	171	210	261
12	127	126	68	177	90	65	59	91	115	136	116	121	122	148	192
13	179	177	110	152	187	162	149	166	186	204	200	213	218	244	283
14	284	296	234	173	310	288	277	292	310	327	327	341	338	369	410
15	128	178	172	340	300	273	237	215	214	215	251	284	332	326	325
16	0	54	90	319	198	174	135	100	91	89	130	166	224	207	199
17	54	0	68	300	149	126	89	49	38	39	76	111	172	153	149
18	90	68	0	234	128	100	66	60	77	94	99	125	159	164	184
19	319	300	234	0	227	219	233	269	293	314	289	284	245	293	354
20	198	149	128	227	0	28	64	99	116	133	88	65	32	68	128
21	174	126	100	219	28	0	38	77	98	116	77	55	60	84	136
22	135	89	66	233	64	38	0	41	65	85	57	66	64	99	134
23	100	49	60	206	99	77	41	0	24	45	39	69	124	111	123
24	91	38	77	293	116	98	65	24	0	21	38	74	138	115	116
25	89	39	94	314	133	116	85	45	21	0	49	83	151	123	110
26	130	76	99	289	88	77	57	39	38	49	0	36	104	77	86
27	166	111	125	284	65	65	66	69	74	83	36	0	72	42	71
28	224	172	159	245	32	60	64	124	138	151	104	72	0	54	121
29	207	153	164	293	68	84	99	111	115	123	77	42	54	0	67
30	199	149	184	354	128	136	134	123	116	110	86	71	121	67	0
31 - 52	193	152	110	182	48	36	64	105	128	148	112	101	76	114	171

APPENDIX 2

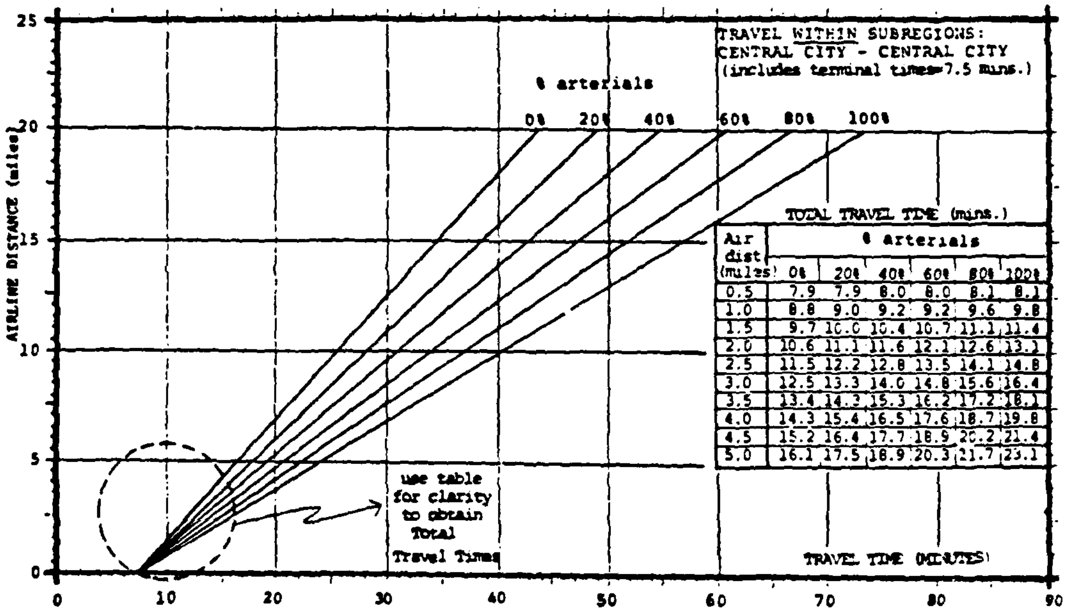
Cost Values for all Workers (Millimeters)

C_{ij}(mm)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	113	60	80	140	102	280	225	312	579	452	392	443	665	722
2	113	0	172	48	246	153	285	303	232	471	340	303	337	553	642
3	60	172	0	132	81	104	281	186	354	634	512	451	503	727	775
4	80	48	134	0	204	106	250	255	237	501	383	348	383	596	590
5	140	246	81	204	0	132	276	129	402	701	586	530	582	801	853
6	102	153	104	106	132	0	180	152	269	579	483	454	487	687	794
7	280	285	281	250	276	180	0	191	232	620	580	586	586	740	917
8	225	303	186	255	129	152	191	0	380	120	635	603	639	834	947
9	312	232	354	237	402	269	232	380	0	433	453	498	435	534	772
10	587	470	684	452	799	544	601	796	531	0	96	169	120	128	304
11	511	390	613	385	735	499	612	762	602	96	0	73	171	170	253
12	474	376	575	373	702	493	641	753	670	169	73	0	297	222	230
13	566	451	668	449	795	567	682	830	640	120	71	97	0	128	189
14	681	560	785	555	907	774	729	918	640	128	170	222	128	0	238
Worker(i) 15	694	605	789	605	915	782	862	987	834	304	253	230	189	238	0
16	584	527	676	517	804	671	795	877	815	295	213	157	179	284	128
17	532	488	621	473	750	617	752	827	795	283	193	126	177	296	178
18	519	440	615	436	745	612	709	810	729	215	127	68	110	234	172
19	563	459	662	431	770	637	556	658	497	46	108	177	152	173	340
20	390	375	488	334	617	484	610	680	703	538	398	320	376	606	640
21	417	373	516	348	646	513	627	708	702	524	380	295	351	584	613
22	454	402	558	385	680	547	664	746	722	531	385	289	338	573	577
23	484	443	575	425	702	569	705	777	760	562	417	321	355	588	555
24	496	466	584	446	711	578	725	791	784	586	440	345	375	606	554
25	510	486	593	464	718	585	744	803	805	606	460	366	393	623	555
26	462	449	546	416	672	539	698	754	775	987	441	346	389	623	591
27	428	436	510	397	636	503	676	719	767	588	443	351	402	637	624
28	361	393	456	335	585	452	600	653	717	560	424	352	407	634	672
29	398	442	472	388	594	461	648	680	770	605	463	378	433	665	666
30	460	503	518	454	631	498	713	728	833	660	514	422	472	706	665
31 - 40	59	47	59	47	80	101	179	128	231	430	337	292	334	531	551
41 - 47	358	370	453	331	582	409	553	650	494	[illegible]	70	67	70	127	127
48 - 52	358	370	453	331	582	409	553	650	494	430	337	292	334	531	551

C_{ij}(mm)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	591	520	441	591	211	241	276	296	322	349	254	119	200	209	284
2	543	485	371	496	205	206	233	264	301	334	250	216	241	262	336
3	641	567	495	648	267	298	330	345	368	390	296	239	253	241	380
4	581	518	415	516	212	229	264	294	329	360	265	225	231	256	335
5	721	648	577	708	348	380	412	424	447	467	374	317	334	315	365
6	679	612	517	582	296	323	359	387	417	445	351	298	294	310	385
7	829	767	658	611	458	478	513	544	578	610	517	468	466	486	564
8	816	747	664	618	433	464	500	521	549	574	478	422	424	423	404
9	732	693	561	435	434	436	454	482	520	554	477	448	466	491	567
10	295	283	215	46	367	356	361	382	420	453	387	367	407	424	492
11	213	193	127	108	278	263	266	288	325	358	292	273	322	333	397
12	157	126	68	177	223	201	193	215	253	287	220	204	273	271	328
13	179	177	110	152	320	298	283	290	324	355	304	296	369	367	419
14	284	296	234	173	443	424	411	416	448	478	431	424	489	492	546
Worker(i) 15	128	178	172	340	433	409	371	339	352	366	355	367	483	449	461
16	0	54	90	319	331	310	269	224	229	240	234	249	375	330	335
17	54	0	68	300	282	262	223	173	176	190	180	194	323	276	385
18	90	68	0	234	261	236	200	184	215	245	203	208	310	287	320
19	319	300	234	0	360	355	367	393	431	465	393	367	396	416	490
20	517	449	362	567	0	28	64	99	116	133	88	65	32	68	128
21	493	426	334	559	28	0	38	77	98	116	77	65	60	84	136
22	454	389	300	573	64	38	0	41	65	85	57	66	64	99	134
23	419	349	294	609	99	77	41	0	24	45	39	69	124	111	123
24	410	338	311	633	116	98	65	24	0	21	38	74	138	115	116
25	408	339	328	654	133	116	85	45	21	0	49	83	151	123	110
26	449	376	333	629	88	77	57	39	38	49	0	36	104	77	86
27	485	411	359	624	65	65	66	69	74	83	36	0	72	42	71
28	543	472	393	685	32	60	64	124	138	151	104	72	0	54	121
29	526	453	398	633	68	84	99	111	115	123	77	42	54	0	67
30	518	449	418	694	128	136	134	123	116	110	86	71	121	67	0
31 - 40	405	335	291	432	202	198	190	170	173	187	177	191	197	206	281
41 - 47	53	53	67	45	202	198	190	170	173	187	177	191	197	206	281
48 - 52	405	335	291	432	27	27	37	23	20	20	35	35	31	41	66

APPENDIX 3

Graphs of Straightline Distance Versus Travel Time

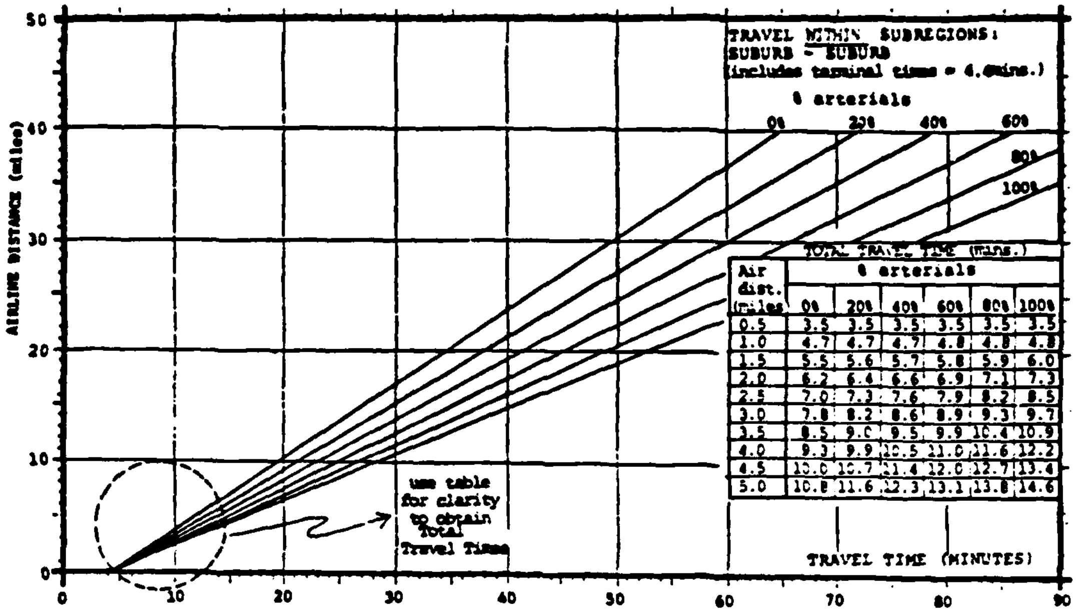


Air dist (miles)	% arterials 0%	20%	40%	60%	80%	100%
0.5	7.9	7.9	8.0	8.0	8.1	8.1
1.0	8.8	9.0	9.2	9.2	9.6	9.8
1.5	9.7	10.0	10.4	10.7	11.1	11.4
2.0	10.6	11.1	11.6	12.1	12.6	13.1
2.5	11.5	12.2	12.8	13.5	14.1	14.8
3.0	12.5	13.3	14.0	14.8	15.6	16.4
3.5	13.4	14.3	15.3	16.2	17.2	18.1
4.0	14.3	15.4	16.5	17.6	18.7	19.8
4.5	15.2	16.4	17.7	18.9	20.2	21.4
5.0	16.1	17.5	18.9	20.3	21.7	23.1

Airline distance vs travel time vs distribution factors, by trip purpose (central city to central city), in urban area of 250,000-750,000 population.

SOURCE: Transportation Research Board

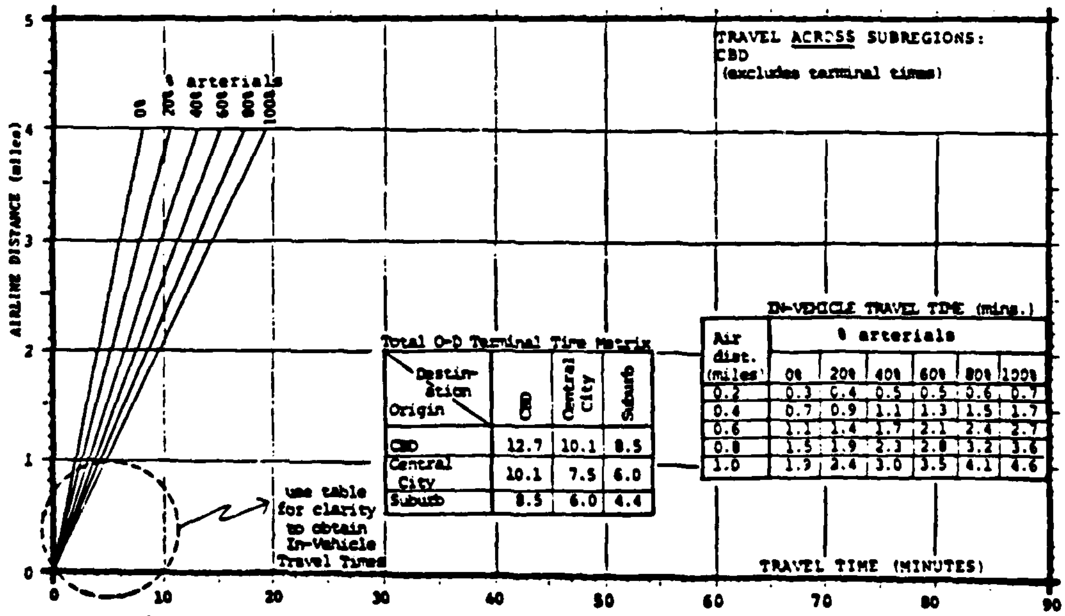
Graphs of Straightline Distance Versus Travel Time



TOTAL TRAVEL TIME (mins.)

Air dist. (miles)	% arterials 0%	20%	40%	60%	80%	100%
0.5	3.5	3.5	3.5	3.5	3.5	3.5
1.0	4.7	4.7	4.7	4.8	4.8	4.8
1.5	5.5	5.6	5.7	5.8	5.9	6.0
2.0	6.2	6.4	6.6	6.9	7.1	7.3
2.5	7.0	7.3	7.6	7.9	8.2	8.5
3.0	7.8	8.2	8.6	8.9	9.3	9.7
3.5	8.5	9.0	9.5	9.9	10.4	10.9
4.0	9.3	9.9	10.5	11.0	11.6	12.2
4.5	10.0	10.7	11.4	12.0	12.7	13.4
5.0	10.8	11.6	12.3	13.1	13.8	14.6

Airline distance vs travel time vs distribution factors, by trip purpose (suburb to suburb), in urban area of 250,000-750,000 population.



Total O-D Terminal Time Matrix

Origin \ Destination	CBD	Central City	Suburb
CBD	12.7	10.1	8.5
Central City	10.1	7.5	6.0
Suburb	8.5	6.0	4.4

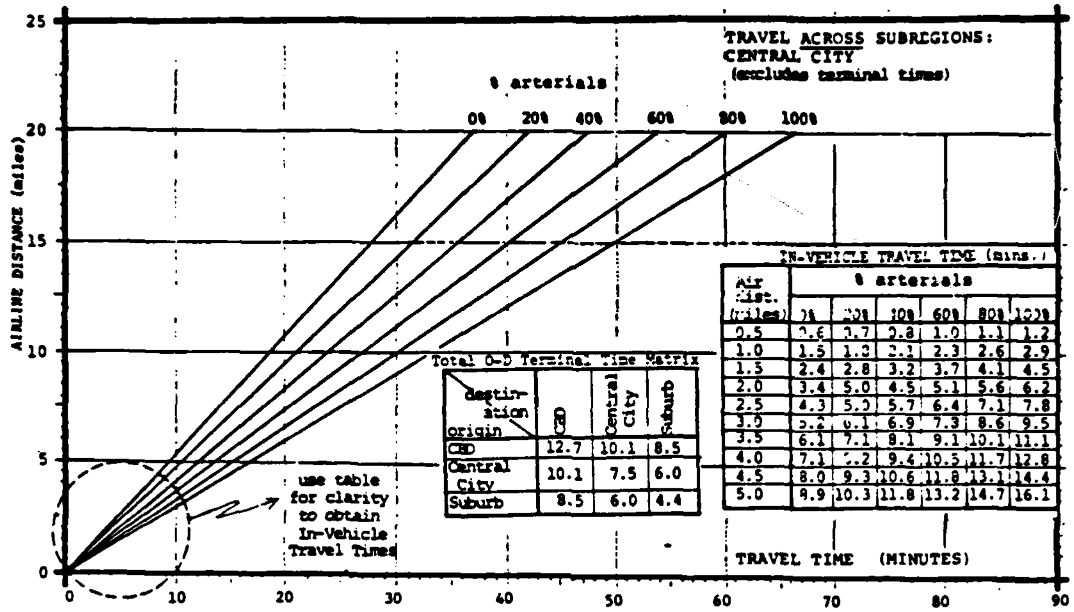
IN-VEHICLE TRAVEL TIME (mins.)

Air dist. (miles)	% arterials 0%	20%	40%	60%	80%	100%
0.2	0.3	0.4	0.5	0.5	0.6	0.7
0.4	0.7	0.9	1.1	1.3	1.5	1.7
0.6	1.1	1.4	1.7	2.1	2.4	2.7
0.8	1.5	1.9	2.3	2.8	3.2	3.6
1.0	1.9	2.4	3.0	3.5	4.1	4.6

Airline distance vs travel time vs distribution factors by trip purpose (CBD), in urban area of 250,000-750,000 population.

SOURCE: Transportation Research Board

Graphs of Straightline Distance Versus Travel Time



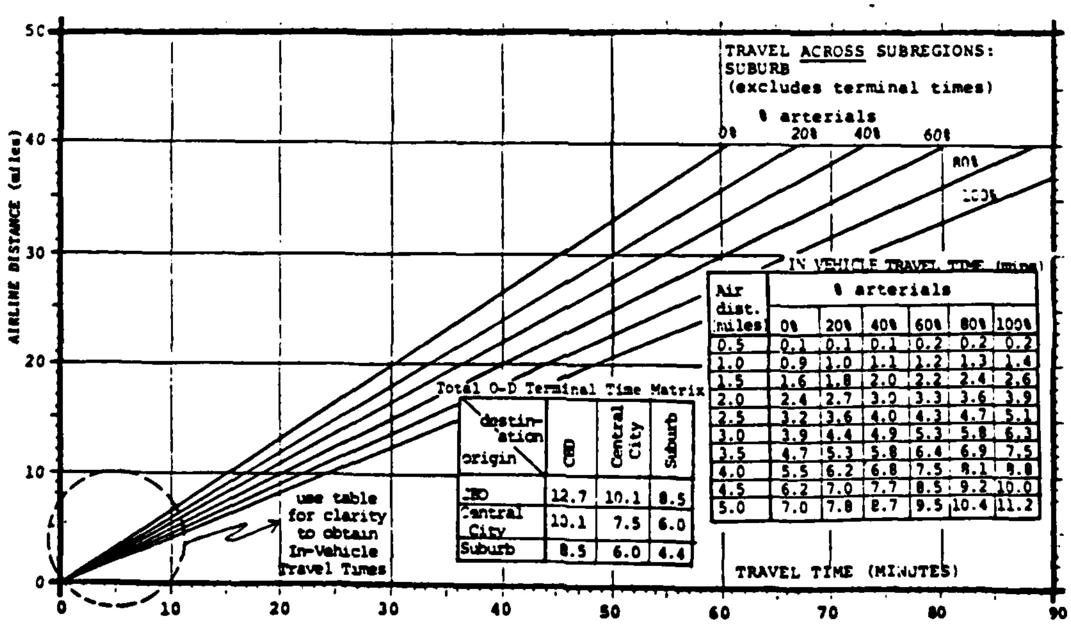
IN-VEHICLE TRAVEL TIME (mins.)

Air dist. (miles)	% arterials 0%	20%	40%	60%	80%	100%
0.5	0.6	0.7	0.8	1.0	1.1	1.2
1.0	1.5	1.8	2.1	2.3	2.6	2.9
1.5	2.4	2.8	3.2	3.7	4.1	4.5
2.0	3.4	5.0	4.5	5.1	5.6	6.2
2.5	4.3	5.0	5.7	6.4	7.1	7.8
3.0	5.2	6.1	6.9	7.3	8.6	9.5
3.5	6.1	7.1	8.1	9.1	10.1	11.1
4.0	7.1	8.2	9.4	10.5	11.7	12.8
4.5	8.0	9.3	10.6	11.8	13.1	14.4
5.0	9.9	10.3	11.8	13.2	14.7	16.1

Total O-D Terminal Time Matrix

origin \ destination	CBD	Central City	Suburb
CBD	12.7	10.1	8.5
Central City	10.1	7.5	6.0
Suburb	8.5	6.0	4.4

Airline distance vs travel time vs distribution factors, by trip purpose (central city), in urban area of 250,000-750,000 population.



IN VEHICLE TRAVEL TIME (mins)

Air dist. (miles)	% arterials 0%	20%	40%	60%	80%	100%
0.5	0.1	0.1	0.1	0.2	0.2	0.2
1.0	0.9	1.0	1.1	1.2	1.3	1.4
1.5	1.6	1.8	2.0	2.2	2.4	2.6
2.0	2.4	2.7	3.0	3.3	3.6	3.9
2.5	3.2	3.6	4.0	4.3	4.7	5.1
3.0	3.9	4.4	4.9	5.3	5.8	6.3
3.5	4.7	5.3	5.8	6.4	6.9	7.5
4.0	5.5	6.2	6.8	7.5	8.1	8.8
4.5	6.2	7.0	7.7	8.5	9.2	10.0
5.0	7.0	7.8	8.7	9.5	10.4	11.2

Total O-D Terminal Time Matrix

origin \ destination	CBD	Central City	Suburb
CBD	12.7	10.1	8.5
Central City	10.1	7.5	6.0
Suburb	8.5	6.0	4.4

Airline distance vs travel time vs distribution factors, by trip purpose (suburb), in urban area of 250,000-750,000 population.

SOURCE: Transportation Research Board

APPENDIX 4

Travel Time Values (Hours X 100)

t_{ij}(hrs)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	18	25	19	25	33	27	52	48	34	38	32	27	39	45	43	31	36	31	34	21	25	29	28	28	28	25	22	19	25	33
2	25	18	29	19	37	34	36	42	31	29	25	22	27	36	40	41	32	25	27	22	27	35	28	31	34	32	33	25	27	43
3	19	29	19	33	25	27	51	32	53	45	38	32	43	53	55	44	39	42	39	33	36	33	35	35	38	35	27	27	24	34
4	25	19	33	19	35	27	42	38	38	54	25	24	32	40	45	41	33	31	31	25	22	33	30	33	44	29	27	25	33	44
5	33	37	25	35	19	33	45	36	49	51	46	42	49	58	62	53	47	48	48	34	37	48	42	44	46	38	47	29	32	40
6	27	34	27	27	33	22	32	36	41	42	38	36	45	51	57	50	48	47	41	29	35	44	44	45	47	39	41	33	45	52
7	52	36	51	42	45	32	14	29	33	40	43	56	52	47	57	57	31	48	32	51	51	54	41	50	54	48	49	43	45	57
8	48	42	32	38	36	36	29	14	45	52	51	47	56	62	67	63	54	51	39	42	46	54	49	52	54	48	43	40	42	50
9	34	31	53	38	49	41	33	45	16	21	22	34	36	31	47	55	49	44	19	38	37	49	45	47	49	46	38	41	44	57
10	38	29	45	54	51	42	40	52	21	19	25	28	25	20	42	42	43	33	19	34	34	43	38	40	41	41	41	39	41	51
11	32	25	38	25	46	38	43	51	22	25	19	22	22	32	37	34	33	27	27	27	27	34	28	32	36	34	37	31	35	46
12	27	22	32	24	42	36	56	47	34	28	22	16	23	31	33	28	25	20	39	22	19	26	21	27	29	27	27	24	25	34
13	39	27	43	32	49	45	52	56	36	25	22	23	20	24	32	34	35	27	29	29	24	38	28	34	37	32	33	36	35	44
14	45	36	53	40	58	51	47	62	31	20	32	31	24	14	31	38	40	31	25	41	37	48	39	40	43	41	42	42	46	53
15	43	40	55	45	62	57	57	67	47	42	37	33	32	31	14	30	31	39	46	40	37	40	46	46	46	47	47	48	50	52
16	31	41	44	41	53	50	57	63	55	42	35	28	34	38	30	17	19	25	45	34	28	40	27	25	25	25	27	38	35	37
17	36	32	39	33	47	48	51	54	49	43	33	25	35	40	39	19	16	22	42	27	28	25	19	16	16	22	23	29	26	36
18	31	25	42	31	48	47	48	51	44	33	27	20	27	31	31	25	22	18	36	28	22	28	20	19	21	22	24	27	27	31
19	34	27	39	31	48	41	32	39	19	19	27	39	29	25	29	45	42	36	16	38	36	42	39	41	46	41	39	38	42	50
20	21	22	33	25	34	29	51	42	38	34	27	22	29	41	40	34	27	28	38	15	16	37	26	29	29	25	22	16	22	30
21	25	27	36	22	37	35	51	46	37	34	27	19	24	37	37	28	28	22	36	16	15	24	26	27	28	22	22	19	25	33
22	29	36	33	33	48	44	54	54	49	43	34	26	28	48	40	40	25	28	42	27	24	24	25	28	30	26	29	28	32	40
23	28	28	35	30	42	44	41	49	45	38	28	21	28	39	46	27	19	20	39	26	26	25	14	16	19	16	19	25	21	30
24	28	31	35	33	44	45	50	52	47	40	32	27	34	40	46	25	16	19	41	29	27	28	16	13	14	16	19	27	25	30
25	28	34	38	44	46	47	54	54	49	41	36	29	37	43	46	25	16	21	46	29	28	30	19	14	13	19	22	31	25	27
26	25	32	35	29	38	39	48	48	46	41	34	27	32	41	47	25	22	22	41	25	22	26	16	16	19	15	16	23	19	25
27	22	33	27	27	37	41	49	43	38	41	37	27	33	42	47	27	23	24	39	22	22	29	19	19	22	16	14	22	15	22
28	19	25	27	25	29	33	43	40	41	39	31	24	36	42	48	38	29	27	38	16	19	28	25	27	31	23	22	14	19	30
29	25	27	24	33	32	45	45	42	44	41	35	25	35	46	50	35	26	27	42	22	25	32	21	25	25	19	15	19	14	22
30	33	43	34	44	40	52	57	50	57	51	46	34	44	53	52	37	36	31	50	30	33	40	30	30	27	25	22	30	22	17
31 - 52	23	18	29	22	36	34	40	43	37	32	23	17	26	36	30	31	29	29	29	17	16	31	26	28	31	23	22	19	27	31

APPENDIX 5

Computer Program Listing for Heuristics

```
C**** Program for Heuristic Procedure.

C**** This program is able to be generalized as long as the dimensions
     Cstatements are entered correctly.

C**** INUMBR is the job number
C     JLOC is the job location
C     ILOC is the worker number and location

C**** N=the number of jobs
C     M=the number of workers
C     L=number of locations
C     NF=the number of floaters.
C     G=the number of the area with the highest intraarea travel time.

C**** ICOST, NCOST and MCOST are the cost matrices for a worker going
     Cfrom location (ILOC) to the job location (JLOC).

C     TRAVTM and NTRVTM are the travel time matrices for a worker going
     Cfrom location (ILOC) to the job location (JLOC).

C     WJOBHR is a matrix in which the row number is the job number
     C(INUMBR) and the job location is the column number (JLOC).  The
     Cvalue within the matrix is the work time required to do that par-
     Cticular job based on the standard work times (WRKTIM).  If the value
     Cis 0 then the job no longer exists.

C    ISNMNT is a matrix used to store the assignments that are made.
    CThe row number indicates the job number (INUMBR) and the column
    Cnumber indicates the worker number (ILOC).  The value within the
    Cmatrix is the location of the job when it is not a 0 (JLOC).

C    The hours and NHOURS arrays store the amount or work time and
    Ctravel time that each worker (ILOC) has available.

C    The TOTHRS array is used to accumulate the amount of time assigned
    Cto each worker (ILOC).

C    The EMPAY array is used to store the pay rate of the workers (ILOC).
```

```
C    DSTNC and XDSTNC are distance matrices for a worker going from
    Clocation (ILOC) to the job location (JLOC).

C*** ICOST, NCOST, and MCOST are M by L, NTRVTM and TRAVTM are M by L,
    CWJOBHR is N by L, ISNMNT is N by M and HOURS, TOTHRS and EMPAY are M.
    CDSTNC and XDSTNC are M by L.

      Dimension ISNMNT (450, 52), WJOBHR (450,30)
      Dimension HOURS (52), NHOURS (52), TOTHRS (52)
      Dimension NTRVTM (52,30), TRAVTM (52,30)
      Dimension ICOST (52,30), NCOST (52,30), MCOST (52,30)
      Dimension EMPAY (52), DSTNC (52,30), XDSTNC (52,30)
      Common N, M, L, NF
      Integer ISNMNT*2
      Integer G
      Real NTRVTM, NHOURS
      Real ICOST, NCOST, MCOST, ISMALL
      N=450

      M=52
      L=30
      NF=22
      G=22
      DO 0 1=1,M
      TOTHRS(I)=0.
    0 Continue
      DO 5 IA=1,N
      DO 1 JB-1,M
      ISNMNT (IA,JB)=0
    1 Continue
    5 Continue
      DO 10 IC=1,M
      Read (5,99) (ICOST(IC,JD),JD=1,L)

C*** To modify the solution procedure, the travel times can be read into
    CICOST rather than the original cost matrix.  This will then select the
    Cjobs according to the smalest travel times.  Additionally the if state-
    Cment in subroutine UPDATE should be removed.
```

```
   99 Format (16F5.0)
   10 Continue
      Write (6,100)
  100 Format (1H0,35X,'initial cost matrix')
      DO 15 IC=1,M
      Write (6,98) (ICOST(IE,JF),JF=1,L)
   98 Format (1H0,16F6.0)
   15 Continue
      DO 25 IG=1,M
      DO 20 JH=1,L
      NCOST (IG,JH)=ICOST (IG,JH)
C**** NCOST is a duplicate matrix for ICOST and used in calculations.
   20 Continue
   25 Continue
      DO 30 II=1,M
      Read (5,97) (TRAVTM(II,JJ),JJ=1,L)
   97 Format (16F5.1)
   30 Continue
      DO 32 IIA=1,M
      DO 31 JJA=1,L
      TRAVTM (IIA,JJA)=TRAVTM(IIA,JJA)/60.00
   31 Continue
   32 Continue
C**** Dividing the TRAVTM matrix by 60 converts minutes to hours for
     Cstandardization within the program.
      DO 34 ILOC=1,M
      Read (5,96) (DSTNC(ILOC,JLOC),JLOC=1,L)
   96 Format (16F5.2)
   34 Continue
      DO 33 ILOC=1,M
      DO 133 JLOC=1,L
      DSTNC(ILOC,JLOC)=DSTNC(ILOC,JLOC)*1.22
C**** Multiplying by the circuity factor converts straight line distance
     Cto actual driving distance.
  133 Continue
   33 Continue
      DO 35 JL=1,L
      NTRVTM (IK,JL)=TRAVTM(IK,JL)
C**** NTRVTM is a duplicate matrix for TRAVTM and used in calculations.
   35 Continue
   36 Continue
```

```
      DO 38 IKA=1,M
      DO 37 JLA=1,L
      XDSTNC (IKA,JLA)=DSTNC(IKA,JLA)
   37 Continue
   38 Continue
C**** DSTNC  is a duplicate matrix for DSTNC and used in calculations.
      DO 40 IM=1,M
      Read (5,95) HOURS(IM) EMPAY(IM)
   95 Format (F5.1,F5.2)
   40 Continue
      DO 41 I=1,M
      IF(I.GT.(M-NF)) HOURS(I)=HOURS(I)-(TRAVTM(G,G)+.50)
      IF(I.LE.(M-NF)) HOURS(I)=HOURS(I)—(TRAVTM(I,I)+.50)
     C-(TRAVTM(M-NF+1),I)-TRAVTM(I,I))
      IF(HOURS(I).LT.O) HOURS(I)=0.
   41 Continue
C**** This loop ensures each worker will have enough time to do one
     Cemergency job in his assigned area.
      Write (6,94)
   94 Format (1H1)
      Write (6,93)
   93 Format (1HO,35X,'Travel time')
      DO 45 IN=1,M
      Write (6,92) (TRAVTM(IN,JD),JO=1,L)
   92 Format (1HO,16F6.2)
   45 Continue
      Write (6.192)
  192 Format(1H1,34X,'Driving distance matrix')
      DO 46 INA=1,M
      Write (6,193) (DSTNC(INA,JOA),JOA=1,L)
  193 Format (1HO,16F6.2)
   46 Continue
      DO 49 IR=1,N
      DO 48 JS=1,L
      IFRASN (IR,JS)=0
   48 Continue
   49 Continue
      Write (6,102)
  102 Format (1H1,6X,'initial worker hours')
      K=0
      DO 50 IP=1,M
      K=K+1
```

```
      Write (6,91) K,HOURS(IP),EMPAY(IP)
   91 Format (1H0,I5,5X,F5.2,5X,F5.2)
   50 Continue
      DO 52 IR-1,N
      DO 51 JS=1,L
      WJOBHR(IR,JS)=0.
   51 Continue
   52 Continue
      DO 53 IRA=1,N
      Read (5,90) IWRKR,JS,VALU,IR
      WJOBHR(IR,JS)=VALU
   90 Format (2I5,F5.0,I5)
   53 Continue
   65 Continue
      Call SMLCST(NCOST,ILOC,JLOC,ISMALL,HOURS)
      If (ISMALL,EQ.999.) go to 75
C**** If ISMALL equals 999, then there are no more jobs or workers
     Cavailable.
      Call FNDJOB (WJOBHR,INUMBR,JLOC,NCOST,WRKTIM,DUMMYA)
      If (WRKTIM.LE.0.) go to 65
C**** If there are still jobs to be done, then work time (WRKTIM) will
     Cnot be 0.

      Call WRKHRS (NCOST,WJOBHR,INUMBR,ILOC,JLOC,HOURS,WRKTIM,INSMNT,
     CNTRVTM,TOTHRS,ISMALL,ICOST,TRAVTM)
   70 Go to 65
   75 Continue
      Write (6,104)
  104 Format (1H1,10X,'assignment list')
      K=0
      DO 81 JW=1,M
      K=K+1
      Write (6,105) K
  105 Format (1H0,'worker',I5,8X,'job number',16X,'location')
      DO 80 IV=1,N
      IVALUE=ISNMNT(IV,JW)
      If (IVALUE.LE.0) go to 80
      Write (6,106) IV, IVALUE
  106 Format (1H0,20X,I5,20X,I5)
   80 Continue
   81 Continue
      Write (6,107)
```

```
107 Format (1H1,2X,'worker hours remaining')
    K=0
    DO 82 IX=1,M
    K=K+1
    Write (6,108) K,HOURS(IX)
108 Format (1H0,'worker',I5,5X,'hours',F5.2)
 82 Continue
    TOTAL=0.
    TVTOTL=0.
    EMTOTL=0.
    DO 84 INUMBR=1,N
    DO 185 ILOC=1,M
    JLOC=ISNMNT(INUMBR,ILOC)
    If (JLOC.EQ.0) go to 184
    I=ILOC
    J=JLOC
    SBTOTL=XDSTNC(I,J)*.25
    TVTOTL=SBTOTL+TVTOTL
    If (J.EQ.I) go to 184
    DO 83 JX=1,L
    XDSTNC(ILOC,JX)=DSTNC(JLOC,JX)
 83 Continue
184 Continue
185 Continue
 84 Continue
    DO 85 IZ=1,M
    FSTOTL=EMPAY(IZ)*TOTHRS(IZ)
    EMTOTL=FSTOTL+EMTOTL
 85 Continue
    TOTAL=EMTOTL+TVTOTL
    Write (6,109) Total
109 Format (1H1,'total cost of assignments',5X,'$',F8.2)
    Write (6,110)
110 Format (1H1)
    Stop
    End
    Subroutine SMLCST(MCOST,IX,JY,ISMALL,HOURS)
    Dimension NCOST(52,30),MCOST(52,30),HOURS(52)
    Real NTRVTM,NHOURS
    Real ICOST,NCOST,MCOST,ISMALL
    Common N,M,L,NF
    ISMALL=MCOST(1,1)
    IX=1
```

```
      JY=1
      DO 20 I=1,M
      DO 15 J=1,L
      If(MCOST(I,J).GE.ISMALL) go to 15
      ISMALL=MCOST(I,J)
      IX=I
      JY=J
   15 Continue
   20 Continue
      Return
      End
C**** Subroutine SMLCST is used to calculate the smallest value in the
     Ccost matrix at a given point in time.  As the matrix is updated
     Cthis value will change.
      Subroutine FNDJOB(WJOBHR,INUMBR,JLOC,NCOST,XTIME,YTIME)
      Dimension WJOBHR(450,30)
      Dimension NCOST(52,30)
      Real NTRVTM,NHOURS
      Real ICOST,NCOST,MCOST,ISMALL
      Common N,M,L,NF
      DO 15 INUMBR=1,N
      XTIME=WJOBHR(INUMBR,JLOC)
      If (XTIME,GT.0.) go to 5
C**** If the work time (XTIME) is greater than 0, then there is a job
     Cthat needs assigned.
   15 Continue
      INUMBR=INUMBR-1
      DO 10 I=1,M
      NCOST(I,JLOC)=999.
C**** If no more jobs exist in location (JLOC), then it must be eliminated
     Cfrom further consideration.
   10 Continue
    5 Continue
      If (XTIME.EQ.1.) XTIME=.33
      If (XTIME.EQ.2.) XTIME=.50
      If (XTIME.EQ.3.) XTIME=.83
      If (XTIME.EQ.4.) XTIME=.25
      YTIME=XTIME
      Return
      End
```

```
C**** Subroutine FNDJOB is used to see if there is a job for the lowest
     Ccost in the NCOST matrix.  If no jobs remain then the value in the
     Cmatrix is set larger than any other.
      Subroutine WRKHRS (NCOST,WJOBHR,INUMBR,ILOC,JLOC,HOURS,WRKTIM,
     CISNMNT, NTRVTM,TOTHRS,ISMALL,ICOST,TRAVTM)
      Dimension ISNMNT(450,52),WJOBHR(450,30)
      Dimension NCOST(52,30),HOURS(52)
      Dimension NTRVTM(52,30)NHOURS(52),TOTHRS(52)
      Dimension ICOST(52,30),TRAVTM(52,30)
      Dimension XTRVTM(52,30)
      Integer ISNMNT*2
      Real NTRVTM, NHOURS
      Real ICOST,NCOST,MCOST,ISMALL
      Common N,M,L,NF
      DO 2 I=1,M
      DO 3 J=1,L
      XTRVTM(I,J)=NTRVTM(I,J)
    3 Continue
    2 Continue
C**** XTRVTM is a duplicate matrix for NTRVTM and used in calculations.
      XTIME=0.
      J=JLOC

      X=0.
      K=ILOC
      DO 14 IB=1,M
      SUMTIM=0.
      TOTTIM=0.
      If (NCOST(IB,J).NE.NCOST(K,J)) go to 13
      DO 12 I=1,N
      XRKTIM=WJOBHR(I,J)
      XGITIM=(.101)*WRKTIM
      If (XRKTIM.EQ.0.) go to 12
      TOTTIM=XRKTIM+XTRVTM(IB,J)-XGITIM
      SUMTIM=SUMTIM+TOTTIM
      DO 1 JG=1,L
      XTRVTM(IB,JG)=NTRVTM(J,JG)
    1 Continue
   12 Continue
      If (SUMTIM.LE.HOURS(IB)) ILOC=IB
      If (SUMTIM.LE.HOURS(IB)) go to 4
   13 Continue
   14 Continue
```

```
C**** This loop checks to see if there is a worker with the same cost.
     CIf this worker can complete all the jobs remaining in the area,
     Che is considered first.
      DO 0 I=1,M
      Z=HOURS(I)
      If (Z.LE.X) go to 0
      If (NCOST(I,J).EQ.ISMALL) X=HOURS(I)
      If (NCOST(I,J).EQ.ISMALL) ILOC=I
    0 Continue
C**** This loop checks to see if there is another worker who has the same
     Ccost but more time.  If there is then this worker will be assigned
     Cas many jobs as possible before the other worker is looked at again.
    4 Continue
      DO 5 I=1,M
      NHOURS(I)=HOURS(I)
    5 Continue
    6 Continue
      CGITIM=(.101)*WRKTIM
C**** CGITIM is a factor which reduces the amount of work time used by 10.1%.
      NHOURS(ILOC)=HOURS(ILOC)-WRKTIM-NTRVTM(ILOC,JLOC)+CGITIM
      If (NHOURS(ILOC).LT.O.) NCOST(ILOC,JLOC)=999.
C**** This updates the NCOST matrix at this point so that the worker will
     Cnot be considered for the same job time and again.
      If (NHOURS(ILOC).LT.O.) go to 10
      If (NHOURS(ILOC).GE.O.) TOTHRS(ILOC)=TOTHRS(ILOC)+WRKTIM
     C+NTRVTM(ILOC,JLOC)-CGITIM
      If (NHOURS(ILOC).GE.O.) HOURS(ILOC)=NHOURS(ILOC)
      If (NHOURS(ILOC).GE.O.) call ASSIGN (WJOBHR,ISNMNT,ILOC,JLOC,
     CINUMBR,NCOST,ICOST,NTRVTM,TRAVTM)
      If (NHOURS(ILOC).GE.O.) call FNDJOB(WJOBHR,INUMBR,JLOC,NCOST,
     CXTIME,WRKTIM)
      If (XTIME.GT.O.) go to 6
C**** The worker with the smallest cost is assigned to jobs in a location
     Cuntil there are no more jobs or he is out of time.
   10 Continue
      JF=JLOC
      DO 20 IE=1,M
      If (WRKTIM+NTRVTM(IE,JF)-CGITIM.LE.HOURS(IE)) go to 50
   20 Continue
      Write (6,99) WRKTIM,INUMBR
   99 Format (1H1,'overtime',F5.2,5X'job#', I5)
```

```
      Write (6,98)
   98 Format (1H1)
      WJOBHR(INUMBR,JLOC)=0.
C**** If the job (INUMBR) is to be done on overtime then it need not be
     Cconsidered again so its value in the WJOBHR matrix can be set equal
     Cto 0.
   50 Continue
      Return
      End
C**** Subroutine WRKHRS is used to see if the worker related to the
     Csmallest cost has enough time to travel to the job and complete
     Cthe required work.  If he does then his hours are updated and the
     Cassignment will be made.  If the worker does not have the time
     Cthen all other workers are checked.  If none of them have the
     Ctime then an overtime requirement is printed.  If they do have
     Cthe time then the next smallest value is the cost matrix must
     Cbe found.
      Subroutine ASSIGN (WJOBHR,ISNMNT,ILOC,JLOC,INUMBR,NCOST,ICOST,
     CNTRVTM,TRAVTM)
      Dimension ISNMNT(450,52),WJOBHR(450,30)
      Dimension ICOST(52,30),TRAVTM(52,30)
      Dimension NCOST(52,30),NTRVTM(52,30)
      Integer ISNMNT*2
      Real NTRVTM,NHOURS
      Real ICOST,NCOST,MCOST,ISMALL
      Common N,M,L,NF
      ISNMNT (INUMBR,ILOC)=JLOC
      WJOBHR(INUMBR,JLOC)=0.
C**** Once the job (INUMBR) is assigned, it does not have to be
     Cconsidered again.  So its value in the WJOBHR matrix can be set
     Cequal to 0.
      If (ILOC.NE.JLOC) call UPDATE (ILOC,JLOC,NCOST,ICOST,NTRVTM,TRAVTM)
C**** If the worker location (ILOC) is the same as the job location
     C(JLOC), then the worker is already in the proper area and no
     Cupdating of the cost or travel matrices is necessary.
      Return
      End
C**** Subroutine ASSIGN is used to store the assignments as they are
     Cmade and the row value is the job number.  The column number is
     Cthe worker and the value is the location.
      Subroutine UPDATE (ILOC,JLOC,NCOST,ICOST,NTRVTM,TRAVTM)
      Dimension NCOST(52,30),ICOST(52,30)
```

```
      Dimension NTRVTM(52,30),TRAVTM(52,30)
      Real NTRVTM,NHOURS
      Real ICOST,NCOST,MCOST,ISMALL
      Common N,M,L,NF
      If (ILOC.GE.(M-NF)) go to 20
C**** Floater costs in the NCOST matrix do not change with assignments
     Cas these individuals remain as floaters throughout the problem.
     CThis will ensure that they are assigned prior to the other
     Cworkers.
      DO 10 JL=1,L
      NCOST (ILOC,JL)=ICOST(JLOC,JL)
   10 Continue
   20 Continue
      DO 30 JL=1,L
      NTRVTM(ILOC,JL)=TRAVTM(JLOC,JL)
   30 Continue
      Return
      End
C**** Subroutine UPDATE is used to update the working matrices NCOST
     Cand NTRVTM.  This is done so that as the worker moves from his
     Cposition to a new one the proper cost and travel times at that
     Clocation are reflected.
```

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